AN ASSESSMENT OF THE PASSIVHAUS STANDARD FOR A HOT AND ARID CLIMATE: A CASE STUDY IN QATAR

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بسم الله الرحمن الرحيم

Declaration

I certify that this thesis constitutes my own work/investigation, except where otherwise stated; other sources are acknowledged by explicit references.

I declare that this thesis describes original work that has not previously been presented for the award of any other degree of any institution.

Signed: May Khalfan

Date: 1 June 2017

Abstract

Residential and commercial buildings have been identified as major contributors to global energy consumption. This has resulted in integrating energy efficiency measures into most, if not all, new builds in developed countries. Additionally, with the alarming warnings of climate change, buildings are expected to consume even more energy in the future to sustain living standards. In future, buildings need to be designed to achieve energy savings and integrate diverse energy sources. This can be achieved by constructing low energy or zero energy buildings. The German Passivhaus standard has gained ground in this area, with Passivhaus buildings spreading widely worldwide. The Passivhaus's reputation and success have reached the coasts of the Persian Gulf (Arabian Gulf), persuading a green building council and a real estate developer to examine the feasibility of the standard in the hot and arid climate of Qatar. The experimental project, completed in 2013, was composed of a Passivhaus building and a conventional building. This thesis investigates the feasibility of the standard in the context of Qatar by comparing the performance of the two buildings in terms of (1) energy savings, (2) thermal comfort and (3) the thermal envelope performance, using dynamic thermal simulations and real-time monitored data. The assessment process was carried out for the present time and for future climate scenarios. The lack of energy efficiency measures in the residential sector in Qatar and the Gulf Cooperation Council (GCC) countries, in general, was the main motivator of this research. In conducting the research, the challenges of building to the Passivhaus standard in Qatar, based on the specific Qatari experience and a review of the relevant literature, were considered. The findings highlighted the potential of building to the Passivhaus standard. The Qatari Passivhaus building required half the total energy to operate and almost one-third of the energy required to cool the conventional building, and this was evident for both the current and the future scenarios. The highly insulated envelope was responsible for maintaining a consistent indoor temperature and even contributed to achieving temperatures lower than the extreme outdoor dry bulb temperature whilst active cooling was deactivated. The research concludes with a number of key features that could possibly be applicable in the context of Qatar, and which highlight the possibility of a promising transition towards low energy buildings that are ready to face the region's future challenges

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This journey has been bound with a number of challenges and unexpected endeavours, but despite this it was a rewarding and enriching experience, and it would not have been the same without all its bounding conditions. I consider myself fortunate to have been surrounded by a supportive system that has not spared any chance to provide the necessary support.

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Table of Contents

Declaration i

Abstract ii

Acknowledgements iii

Table of Contents iv

List of Figures viii

List of Tables xi

List of Abbreviations xii

1 Introduction 1

1.1 Overview 1

1.2 Research Problem 4

1.3 Hypothesis 6

1.4 Research Aims and Objectives 6

1.5 Research Questions 6

1.6 General Methodology 7

1.7 Thesis Outline 9

2 Energy Efficiency in Buildings 12

2.1 Overview 12

2.2 Energy Efficiency, Standards, and Building Performance Certifications 12

2.3 Climate Change and Energy Efficiency 17

2.4 Energy Performance Standards in the GCC 23

2.5 Energy-Efficient Buildings, Technologies, and Techniques 30

2.6 Summary 35

3 The Passivhaus Standard 37

3.1 Overview 37

3.2 The Passivhaus Definition and Historical Background 37
3.3 Passivhaus Criteria and Requirements 41
3.4 The Passivhaus in Europe 46
3.5 The Passivhaus in different climate zones 54
3.6 Passivhaus Buildings in Hot Climates 59
3.6.1 The Austrian embassy in Jakarta, Indonesia 59
3.6.2 The Le-Bois house in Louisiana, USA 61
3.6.3 Passivhaus model in Dubai, UAE 63
3.7 Summary 64
4 Assessment Tools and Methods 67
4.1 Overview 67
4.2 Assessment Framework 68
4.3 Building Simulation Tool 71
4.3.1 Weather data sets 72
4.3.2 Occupancy schedules and profiles 77
4.4 Performance Indices 77
4.5 Thermal Comfort Models 79
4.5.1 Steady-state thermal comfort and the PMV 80
4.5.2 Adaptive thermal comfort 81
4.5.3 Other thermal comfort measurements 83
4.6 On-site Measurements 85
4.6.1 Logger calibration 89
4.7 Summary 92
5 Qatar’s Passivhaus Project 94
5.1 Overview 94
5.2 Qatar’s Housing Stock 95

5.3 Qatar's Energy Policy 97

5.4 Initiating the Passivhaus Project 100

5.5 Qatar's Passivhaus Project 102

5.5.1 Qatar's weather 102

5.5.2 The Passivhaus Villa 104

5.5.3 The Standard Villa 110

5.6 Building Fabric Comparison 113

5.7 Monitored Data 115

5.8 Summary 119

6 The Performance of the Villas 121

6.1 Overview 121

6.2 On-site Measurement Findings 122

6.2.1 Sub-meter energy use 122

6.2.2 Indoor temperature 125

6.2.3 Relative humidity 129

6.3 Current-time Performance Indicators 131

6.3.1 Energy use 132

6.3.2 Thermal comfort 136

6.3.3 Thermal envelope performance 142

6.4 Future Performance Implications 143

6.4.1 Energy use 143

6.4.2 Thermal comfort 145

6.4.3 Thermal envelope performance 152

6.5 Parametric Study 154

6.5.1 Study approach 155

6.5.2 Findings and analysis 156

6.5.3 Parametric study discussion and conclusion 161
6.6 Summary 163
7 Discussion 165
7.1 Overview 165
7.2 Qatar Passivhaus Project vs. Other Passivhaus Projects in Hot Climates 166
7.3 Qatar Passivhaus Performance vs. the Passivhaus Criteria 169
7.3.1 Energy use 171
7.3.2 Thermal comfort 173
7.3.3 Thermal envelope performance 180
7.4 The impact of climate change on the building sector in Qatar and the GCC 181
7.5 Realising Passivhaus Standards in Qatar, Implications, and Key Features 185
7.6 Summary 188
8 Conclusion and Final remarks 191
8.1 Overview 191
8.2 Summary 191
8.3 Research Significance 192
8.4 Research Main Findings 193
8.5 Research Uncertainty and Limitations 201
8.6 Further Work and Final Remarks 203
References 206
Appendix A 232
Appendix B 233
Appendix C 234
Appendix D 236

List of Figures

Figure 1-1 Global energy use by sub-sector (IEA, 2015)..1

Figure 1-2 General research methodology and levels of exploration 8

Figure 2-1 Energy savings since 1973 with energy-efficient measures (IEA, 2008) 13

Figure 2-2 Factors that affect energy consumption (CIBSE, 2012).....................................14

Figure 2-3 GCC countries (Google Maps, 2016)...24

Figure 2-4 GCC CO_2 emissions (metric tons per capita) (World Bank, 2016a) 25

Figure 2-5 Annualised life cycle energy of some generic buildings (Hernandez and Kenny, 2010) 32

Figure 3-1 Passivhaus approach transition for the 21st Century (A R T Architects, 2016) ..38

Figure 3-2 The five basic principles of the Passivhaus standard (Passepedia, 2015)..........41

Figure 3-3 Passivhaus projects in extreme climates (Ciobanu, 2015; Jesse, 2011; Killough, 2014; Meinhold, 2014) 56

Figure 3-4 Main façade of the Austrian embassy in Jakarta (Oettl, 2014)..........................60

Figure 3-5 Jakarta embassy ground and first floor layout (Oettl, 2014) 61

Figure 3-6 Le-Bois house in Louisiana (Saft and Helton, 2012) 62

Figure 3-7 Le-Bois house ground and first floor layout (Saft and Helton, 2012).................63

Figure 3-8 Dubai model Passivhaus building (Schnieders, Feist and Rongen, 2015) 64

Figure 4-1 Building assessment framework..70

Figure 4-2 Qatar’s present climate (Climate Consultant 6.0, 2016)...................................75

Figure 4-3 Average monthly dry bulb temperature for future weather scenarios 76

Figure 4-4 Average monthly relative humidity for future weather scenarios.....................76

Figure 4-5 Acceptable operative temperature ranges for naturally conditioned spaces (CIBSE, 2014)...83

Figure 4-6 Schnieders’ comfort chart (reproduced from (Schnieders et al., 2015)) 85

Figure 4-7 HOBO data logger (ONSET, 2016a)..89

Figure 4-8 Temperature data logger calibration (first logging period) 90

Figure 4-9 Relative humidity logger calibration (first logging period)................................90

Figure 4-10 Temperature data logger calibration (second logging period) 91

Figure 4-11 Relative humidity logger calibration (second logging period) 91
Figure 5-1 Open yard house forms (Nagy, 1997)...95
Figure 5-2 Popular house layouts (Al-Buainain, 1999) 97
Figure 5-3 Climate classification for the region (Peel, Finlayson and McMahon, 2007)...103
Figure 5-4 Average monthly rainfall, mean temperature and relative humidity (QMD, 2016) 104
Figure 5-5 Standard villa in foreground and Passivhaus villa 105
Figure 5-6 Typical villa layout 105
Figure 5-7 Barwa city development location (Google Maps, 2016; Barwa, 2015)...........106
Figure 5-8 PHV interior (movable panels) 108
Figure 5-9 STV central courtyard 110
Figure 5-10 STV external shade 111
Figure 5-11 PHV external wall..114
Figure 5-12 STV external wall 114
Figure 5-13 Data logger positioning 119
Figure 6-1 PHV simulated and measured energy use..124
Figure 6-2 STV simulated and measured energy use 124
Figure 6-3 PHV and STV measured and predicted HVAC energy use 125
Figure 6-4 Average measured and predicted hourly indoor temperature in PHV 127
Figure 6-5 Average measured and predicted hourly indoor temperature in STV............127
Figure 6-6 Average measured and predicted monthly indoor temperature in PHV and STV LIV 128
Figure 6-7 Average measured and predicted hourly relative humidity in PHV................130
Figure 6-8 Average measured and predicted hourly relative humidity in STV 130
Figure 6-9 Average measured and predicted monthly relative humidity levels in PHV and STV LIV...131
Figure 6-10 Monthly electrical power generated through PV panels in PHV 133
Figure 6-11 PHV and STV annual energy use 134
Figure 6-12 Climate Consultant psychrometric chart for Doha, Qatar 137
Figure 6-13 PHV PMV...139
Figure 6-14 STV PMV 140

Figure 6-15 PHV Schnieders' comfort chart 141
Figure 6-16 STV Schnieders' comfort chart 141
Figure 6-17 PHV and STV thermal envelope performance 142
Figure 6-18 PHV and STV energy use 2020, 2050, 2080 144
Figure 6-19 Climate Consultant psychrometric chart for 2080 weather file 146
Figure 6-20 PMV for the PHV during the hottest day 148
Figure 6-21 PMV for the STV during the hottest day 149
Figure 6-22 PHV: Schnieders' thermal comfort charts for the PHV 150
Figure 6-23 STV: Schnieders' thermal comfort charts for the STV 151
Figure 6-24 Future PHV and STV thermal envelope performance 153
Figure 6-25 STV Wall and roof construction composition 155
Figure 6-26 Individual effect of parametric variations on cooling and energy demands .159
Figure 6-27 Combined effect of parametric variations on cooling and energy demands.159
Figure 6-28 Percentages of energy and cooling demand reduction 161
Figure 7-1 Passivhaus climate zones (PHI, 2015a) 171
Figure 7-2 Measured and predicted temp and RH in the PHV during the hottest day 177
Figure 7-3 Measured and predicted temp and RH in the STV during the hottest day 179
Figure 7-4 Total energy use in the PHV and the STV through the different scenarios 184

List of Tables

Table 2-1 GCC revised building regulations (adapted from (Awawdeh and Tweed, 2006; Dubai Electricity and Water Authority, 2015; KAHRAMAA, 2016; MEW, 2015; MEW, 2014b; Saudi Building Code, 2015; Muscat Municipality , 1992)) 26

Table 3-1 Passivhaus criteria (Passepedia, 2015) 44

Table 3-2 The PH three categories of new build and low energy build (reproduced from recent Passivhaus guidelines (PHI, 2015a)) 45

Table 3-3 Passivhaus guidelines for thermal comfort (reproduced from Recent Passivhaus criteria (PHI, 2015a)) 46

Table 3-4 Hygiene and comfort criteria (reproduced from Recent Passivhaus criteria for minimum thermal comfort (PHI, 2015a)) 46

Table 5-1 PHV material and finishes 108

Table 5-2 STV material and finishes 111

Table 5-3 Opaque components 115

Table 5-4 Glazed components 115

Table 5-5 Sub-meter readings 117

Table 5-6 First logging data 118

Table 5-7 Second logging data 118

Table 6-1 PHV and STV actual energy use 123

Table 6-2 PHV and STV cooling demands 145

Table 6-3 Variables used for STV parametric study 157

Table 6-4 Energy demand comparisons for a family of four members 162

Table 7-1 Features of the four Passivhaus buildings 168

Table 7-2 Qatar Passivhaus villa vs. Passivhaus standards based on IES-VE results 170

Table 7-3 Opaque and transparent surfaces’ U- values (adapted from (KAHRAMAA, 2016; PHI, 2015b; PHI, 2015c)) 171

Table 7-4 PHV estimated and measured primary energy demand 172

Table 7-5 PHV and STV estimated cooling loads 183

List of Abbreviations

Bedroom 1 (BR 1)
Bedroom 2 (BR 2)
Building Management System (BMS)
Building Performance Simulation (BPS)
Building Research Establishment Environmental Assessment Methodology (BREEAM)
Chartered Institution of Building Services Engineers (CIBSE)
Climate Change World Weather Generator (CCWorldWeatherGen)
Cooling Degree Days (CDD)
EnergyPlus Weather Data File (EPW)
Global Sustainability Assessment System (GSAS)
Greenhouse Gas (GHG)
Gulf Cooperation Council (GCC)
Gulf Organization for Research and Development (GORD)
High-Performance buildings (HPBs)
Integrated Environmental Solutions –Virtual Environment (IES-VE)
Intergovernmental Panel on Climate Change (IPCC)
International Energy Agency (IEA)
International Passive House Association (iPHA)
Leadership in Energy and Environmental Design (LEED)
Living room (LIV)
Master Bedroom (M BR)
Passive House Institute (PHI)
Passive House Planning Package (PHPP)
Passivhaus (PH)
Passivhaus Villa (PHV)
Percentage of People Dissatisfied (PPD)
Photovoltaic (PV)
Predicted Mean Vote (PMV)
Primary Energy Demand (PE)
Primary Energy Renewable (PER)
Qatar Environment and Energy Research Institute (QEERI)
Qatar Green Building Council (QGBC)
Qatar Meteorology Department (QMD)
Qatar Sustainability Assessment System (QSAS)
Relative Humidity (RH)
Representative Concentration Pathways (RCP)
Special Report on Emissions Scenarios (SRES)
Standard Villa (STV)
Sustainable Energy Research Group (SERG)
Temperature (Temp)
Typical Meteorological Year (TMY)
University of University of California, Los Angeles (UCLA)
Window to Wall Ratio (WWR)
Zero Energy Buildings (ZEBs)

Chapter One
Introduction

1 Introduction

1.1 Overview

Buildings are no longer just a single-skinned shelter that protects humans from extreme weather conditions. Rather, they have become a complex living skin composed of a number of selective layers which correspond effectively to the outer weather and ensure inner comfort. With the advances in technology and living standards, buildings today are expected to satisfy people's living demands' while providing high levels of internal comfort. This trend is expected to continue in the future, especially given that technology and technological advances are expected to be the norm of the future (Pitts, 2008).

By virtue of the modern living styles and the requirements that buildings need to endure, buildings have been distinguished as one of the main contributors of energy use globally. According to an IEA report, buildings both commercial and residential account for 30%-40% of the total final global energy use (Laustsen, 2008). A statistical study carried out from 2002 to 2012 indicated that residential buildings account for 75% of the total energy consumption within the buildings sector, while non-residential buildings account for the remaining 25% (see Figure 1-1) (IEA, 2015). A recent study has also pointed out that buildings alone consume over 74% of the electricity generated in the Middle East and North African countries (Krarti and Ihm, 2016).

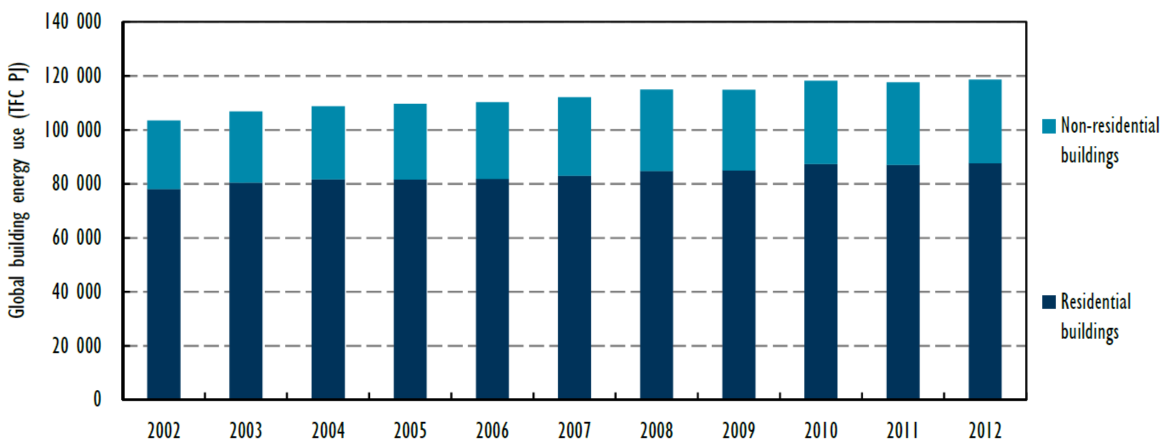


Figure 1-1 Global energy use by sub-sector (IEA, 2015)

The burning of fossil fuels to generate energy for buildings, in addition to other sectors such as industry, transportation, has been identified as one of the main contributors of greenhouse gas (GHG) emissions, which have been linked to climate warming (IPCC, 2015; Jentsch, Bahaj and James, 2008).

Regulating energy use in the built environment, therefore, has become a subject of interest explored by scholars, architects and building engineers for decades, owing to this sector's considerable share of the global energy demand. Energy saving offers a range of benefits: at the local level, it ensures that residents pay less for the energy used; on a national level, it enables countries to sustain energy by cutting down or diversifying energy resources; and on a global level, it contributes towards the mitigation of GHG emissions, which have been linked to climate change. Building codes, rating systems, and energy-efficient typologies have been the main means to achieve energy savings in the built environment.

Developed countries have gained ground by enforcing mandatory energy-efficient measures and by setting future targets to include energy diversity and savings. Additionally, a solid research base was initiated in the West targeting the assessment of various energy-efficient typologies and building codes, with the consideration of creating buildings that could tolerate the inevitable climate change impact. On the other hand, in developing countries energy strategies have only just started to emerge. Although building codes may have existed in many countries from as early as the 1980s, the enforcement of the codes themselves is not evident, especially in the residential sector (Krarti and Ihm, 2016; Iwaro and Mwasha, 2010).

Currently, a sustainable act has been witnessed in the Gulf Cooperation Council (CGG) countries: green building councils are being formed, sustainable and energy-efficient structures are being built, and various studies have started to emerge related to energy saving and the potential of sustainable practices in the area (Akbari, Morsy and Al-Baharna, 1996; Awawdeh and Tweed, 2006; Hertog and Luciani, 2009; Meltzer, Hultman and Langley, 2014; Radhi, 2008; Willis, 2015). However, most of the studies proclaimed energy savings based on a theoretical basis and parametric studies. More recently, in 2013 the first ultra-low energy-efficient building was constructed in Qatar. The building was constructed as part of a scientific project that included two physically similar dwellings, one constructed according to a German energy efficiency standard called Passivhaus (Passepedia, 2015) and named the Passivhaus villa (PHV), and an adjacent building constructed in accordance with a recently adopted rating system in Qatar known as the Global Sustainability Assessment System, GSAS (GORD, 2016), and named the Standard villa (STV).

A Passivhaus building is defined as, *"…a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air"* (Passepedia, 2015). The basis of the Passivhaus standard was derived from previous studies that have focused on achieving low energy use and maximising the benefits of solar energy. The roots of the first inspirations can be traced to China, where a study was commenced to maintain acceptable indoor temperatures without active heating during the cold winter season. The project was carried out by Bo Adamson, a Swedish professor at the University of Lund, who later became the co-originator of the Passivhaus movement (Bere, 2013; Passepedia, 2015). The concept of the Passivhaus building involves a robust building fabric that is highly insulated and airtight, with low thermal transmittance through its opaque and glazed surfaces. Fresh air is drawn into the building through a mechanical ventilation heat-recovery system, which compensates for the lack of air circulation resulting from the airtight building shell, ensuring delivery of fresh air to the building's dry spaces and the extraction of moist air from its wet spaces. Energy savings are ensured in the Passivhaus standard through specific energy-demand benchmarks. Passivhaus buildings are expected to adhere to the outer fabric, thermal comfort and energy-demand criteria in order to achieve the Passivhaus standard.

The Passivhaus standard is not confined to a building type, size or architectural style, and is considered one of the fastest-growing standards around the world. Although it originated in Germany, its typologies have spread far beyond, reaching east to China and Japan, and west to the USA and Canada (Passive House Database, 2014). As of today, more than 50,000 buildings have been constructed according to the standard, most of which are in Europe (Lewis, 2014; iPHA, 2016a). Various assessment and feasibility studies have been conducted to report the validity of the Passivhaus experience in different contexts; some of these studies have even been carried out by the Passivhaus Institute, the official Passivhaus research institution. Many of the studies have indicated that Passivhaus buildings are capable of achieving considerable energy savings, reaching up to 80%, while providing high levels of thermal comfort (Schnieders, 2003; Passive-On, 2007). A number of Passivhaus buildings have been built in hot climates such as southern USA and Indonesia, and in warmer European climates such as Spain, Italy and parts of France (Helton, 2012; Oettl, 2014; Parker, 2009; Passive-On, 2007).

However, it was not until recently that the first Passivhaus experience was tested in the hot and arid climate of the GCC region. The Passivhaus project in Qatar provides first-hand experience of the performance of Passivhaus buildings in the area. It also provides a possible template for future ultra-low-energy building types for the area in an era when temperature rise is being accounted for, and with a changing climate that sets more challenges for buildings, requiring them to be more robust to withstand the change. The Passivhaus approach is considered by many to be the template for future-proofing buildings; its stringent standards and highly articulated building fabric provide the basis for the robust building fabric of future buildings (Carlucci, Zangheri and Pagliano, 2013; Hopfe and McLeod, 2015; Mlecnik, Kaan and Hodgson, 2008; Schnieders and Hermelink, 2006). This thesis is built on the basis of evaluating the performance of the first Passivhaus building in Qatar.

1.2 Research Problem

As described earlier, energy efficiency in the built environment has been realised as the means for achieving energy savings and mitigating GHG emissions. It has also been viewed as the basis for future buildings to sustain energy use and ensure that they can operate effectively under the impact of climate change. This had led to the emergence of a number of energy-efficient typologies targeting energy reduction in the built environment, such as low energy buildings, zero energy buildings, positive buildings and Passivhaus buildings. Simultaneously, buildings codes and targets have been updated or developed to ensure further energy savings and to sustain the environment, warranting a reduction in GHG emissions and a smooth transition to a renewable energy economy. In the past 26 years, Passivhaus buildings have been built and tested around the world, although almost half of the globally built Passivhaus building stock is in Germany (iPHA, 2016). The Passivhaus approach is regarded as one of the most stringent energy-efficient standards; it has been cited by many as one of the fast-growing approaches in the area of energy-efficient standards and has been viewed by others as the blueprint for the future of buildings (Harvey, 2013; Ionescu et al., 2015; Ridley et al., 2014).

The Passivhaus approach has been tested and evaluated in various locations within Europe. Within the CEPHEUS project alone, 250 Passivhaus buildings were constructed as part of a scientific project in nine different cities within five European countries (CEPHEUS, 2001; Schnieders, 2003; Schnieders and Hermelink, 2006). In addition, many other individual assessments have been carried out throughout Europe evaluating the performance of the building and the occupant satisfaction (Brunsgaard, Knudstrup and Heiselberg, 2012; Junghans and Berker, 2014; Mahapatra and Olsson, 2015; Mahdavi and Doppelbauer, 2010; Raidea, Kalameesa and Mauringb, 2015; Ridley et al., 2013). Outside Europe, however, only a few studies have reported the actual feasibility of buildings built according to the Passivhaus approach, mainly in the US (Helton, 2012; Parker, 2009).

While the Passivhaus approach continued to spread to different parts of the world, in the GCC, in 2006, an environmental awareness movement was initiated. Although prescriptive codes existed earlier, enforcement laws were mainly only binding for governmental buildings (Awawdeh and Tweed, 2006; Cooke, 2015; Willis, 2015). As a result of this movement, a number of sustainable public buildings started to appear. However, they were considered very limited in comparison to the booming construction industry in the area (Sabie, Pitts and Nicholls, 2014).

This research addresses the lack of energy-efficient measures in the residential buildings sector in Qatar, a member of the GCC countries, by proposing the Passivhaus experience as a potential solution. The Passivhaus experiment in Qatar, therefore, becomes the key element of this study, with the focus on four main aspects: (1) evaluating the energy savings achieved by applying Passivhaus criteria, (2) assessing the levels of thermal comfort achieved, (3) investigating the importance of addressing the building fabric in accordance with the Passivhaus criteria, and (4) defining how resilient the Passivhaus option could be for the climate of Qatar.

1.3 Hypothesis

The hypothesis of this thesis is that *"the Passivhaus standard could be a potential low energy prototype applicable within the residential sector for the climate of Qatar in the present day and for the future*".

1.4 Research Aims and Objectives

The main focus of this study is to investigate the potential benefits, in terms of energy savings and thermal comfort, if the Passivhaus energy-efficient model was to be incorporated in to the residential sector in Qatar and the GCC. The study, therefore, targeted a number of aims and objectives, as listed below:

1. To propose an energy-efficient model that could be suitable for application in the climate of Qatar.
2. To identify energy-efficient models that have been applied internationally.
3. To recognise the success story of the Passivhaus standard and understand the reasons behind its widespread acceptance internationally.
4. To investigate the energy saving achieved by applying Passivhaus criteria to a test building in Qatar.
5. To assess thermal comfort levels in the Passivhaus building, and how they could be measured in relation to thermal comfort levels in a standard building.
6. To explore how Passivhaus buildings in Qatar could withstand the impact of climate change.
7. To detect the possible challenges that could be associated with the implementation of the Passivhaus standard in Qatar.

1.5 Research Questions

In association with the aims and objectives mentioned above, this study targets to answer the following main research question:

How well will a dwelling built to the Passivhaus standard in Qatar perform, both now and in the future?

The following sub-questions are designed to work towards answering the main research question:

1. *What is the importance of introducing the Passivhaus standard as an energy-efficient model for Qatar?*
2. *How to effectively measure the performance of the Passivhaus building and ensure that its predicted performance reflects the possible actual performance?*
3. *How well does the Passivhaus building perform in comparison to the standard building in the Passivhaus project Qatar?*
4. *If the Passivhaus building was expected to perform better than the standard building at the present time, how well is it expected to perform under the impact of climate change?*
5. *What key features of the Passivhaus building can be transferred to local buildings to improve their performance and sustainability?*
6. *Are Passivhaus buildings expected to be more comfortable than standard buildings, given that people are expected to acclimatise to higher comfort temperatures in hot regions?*
7. *Has the Passivhaus villa actually met the German Passivhaus criteria?*
8. *How does the Passivhaus villa performance compare to that of a conventional residential building in Qatar?*
9. *What are the barriers that may be associated with the implementation of the Passivhaus concept in Qatar?*

1.6 General Methodology

To address the research questions a general framework was established which included analytical and empirical exploration in an attempt to evaluate the performance of the Passivhaus project in Qatar. The following levels of exploration were undertaken (see Figure 1-2) to thoroughly address the performance of the Passivhaus building, as follows:

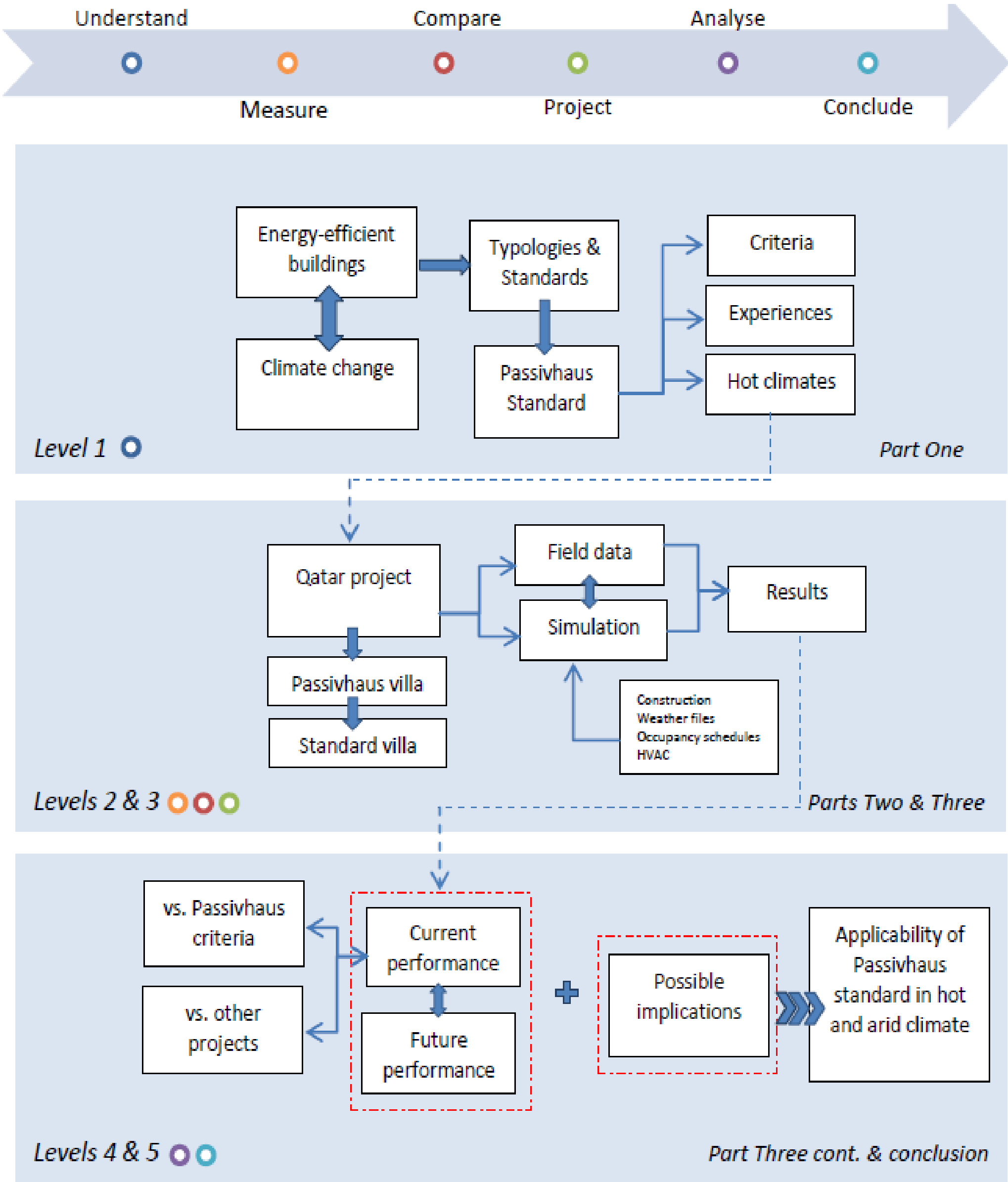


Figure 1-2 General research methodology and levels of exploration

Level 1. Obtain the contextual background knowledge necessary in the area of energy-efficient buildings in general and the Passivhaus approach in particular through a ***literature review***.

Level 2. Evaluate the performance of the Passivhaus building through ***comparative and analytical investigations*** using dynamic simulation and historical weather data.

Level 3. Validate the results through ***empirical evidence*** by employing real-time data.

Level 4. Predict the future performance of the Passivhaus building through ***comparative and analytical investigations*** using dynamic simulation and future weather data sets.

Level 5. Assess the overall applicability of the standard and the probable implications related to its implementation in Qatar through an ***analytical and critical review*** based on the literature review and findings.

The methods and tools that were used in each level are discussed in more detail in Chapter Four.

1.7 Thesis Outline

This thesis has been broken down into three main parts; the three parts follow this introduction chapter and are summarised by the conclusion and final remarks chapter. The chapters are constructed to include an opening overview, which presents an introductory statement and introduces the outline of the chapter. At the end of each chapter, a summary section is included which recaps the main ideas of the chapter and introduces the subsequent chapter. The following is a brief outline of the contents of each part.

Part One (contextual review): this part comprises ***Chapters Two*** and ***Three***, which contain the necessary background literature that sets out the context on which this study rests. Chapter Two involves a review of energy efficiency in the built environment, comprising sections related to energy-efficient measures, typologies, codes, and standards; it also presents the importance of seeking energy efficiency in light of climate change. The chapter showcases the energy-saving trends and policies adopted worldwide and in the Gulf Cooperation Council (GCC). Chapter Three expands to detail the Passivhaus approach, its evolution and implementation in varying contexts. The chapter includes the recent Passivhaus criteria and the main concepts that are to be applied. It also presents a number of studies and findings that evaluated the performance of Passivhaus buildings mainly within Europe. Finally, a number of Passivhaus case studies in hot climates are highlighted at the end this chapter.

Part Two (descriptive review): this part comprises ***Chapters Four*** and ***Five***, which contain a detailed description of the project and the evaluation methods adopted. Chapter Four details the tools and assessment methods which were used to evaluate the performance of the Passivhaus building in Qatar, with the focus on energy use and thermal comfort. The sections include a brief description of the tools and models used and the input parameters required, explaining the reasons behind their specific selection and detailing how they were applied in the study. The chapter also highlights the type of on-site measurements used within this project, as well as explaining the reasons behind the specific selections and methods of use. Chapter Five provides a description of the main case study and the host country. It first gives a brief overview about Qatar, its building stock and energy policy. Later, a detailed description of the project is given, starting from the initiating point when the idea was conceived, then detailing the physical buildings and the real-time data that was collected.

Part Three (analytical review)**:** this part covers ***Chapters Six*** and ***Seven***, containing the findings analysis followed by the discussion chapter. Chapter Six examines the performance of the villas and includes the present and future performance of the Passivhaus villa and the standard villa, with the focus on the three performance indicators selected, i.e. (1) energy use, (2) thermal comfort, and (3) thermal envelope performance. In addition, the chapter presents the findings from the on-site measurement including the sub-meter readings and indoor temperature and relative humidity. The chapter concludes with a parametric study that aims to further assess the performance of the thermal envelope and bridge the gap between the standard and the Passivhaus villa performance through proposing an upgrade to the STV's envelope. Chapter Seven analytically compares the performance of Qatar's Passivhaus villa against the German Passivhaus standard, and against the performance of other Passivhaus projects in hot climates. The chapter ends by presenting possible challenges associated with the implementation of the Passivhaus standard in Qatar and suggests key features that should be applied to the residential buildings stock in Qatar and in the GCC.

Chapter 8**:** this chapter concludes this study by summarising the significance of the research, the main findings, and uncertainties related to the conducted work. It also addresses the hypothesis and research questions and finishes by highlighting possible limitations of the study and future work.

Part 1

Contextual Review

Chapter Two
Energy Efficiency in Buildings

2 Energy Efficiency in Buildings

2.1 Overview

There is increasing evidence that carbon dioxide emissions from the burning of fossil fuels are linked to global warming and climate change (IPCC, 2015). The three main sectors for energy usage are the built environment, transportation and industry. The building sector accounts for around 30% - 40% of the world's total energy consumption, and reducing energy use in buildings through the implementation of energy efficiency measures has become an important theme in recent decades (IEA, 2013b). Developing nations are reaching higher levels of economic and demographic growth, and consequently are demanding more energy in the built environment (Iwaro and Mwasha, 2010). Many programmes carried out by different agencies worldwide are promoting sustainable practices and guidance for developing countries (UNDP, 2016; UNEP, 2016). Developed countries, on the other hand, already have significant experience of energy-efficient, sustainable green building design. Energy-efficient measures and energy targets, along with policies and regulatory codes, have been established within most developed countries (Berardi, 2013; Iwaro and Mwasha, 2010). The following sections will discuss energy efficiency in more detail by demonstrating the approaches leading to energy efficiency measurements. The importance of energy efficiency will then be highlighted in the light of climate change. Finally, a brief summary of the current energy balance in the Gulf Cooperation Council (GCC) countries will be given followed by a short review of a few energy-efficient technologies and schemes that have spread worldwide.

2.2 Energy Efficiency, Standards, and Building Performance Certifications

The Chartered Institution of Building Services Engineers (CIBSE) Energy Efficiency in Buildings guide states: *"An energy efficient building provides the required internal environment and services with minimum energy use in a cost effective and environmentally sensitive manner*" (CIBSE, 2012, p.1.1). Since the oil crises in 1973 many countries have started to adopt a range of built environment energy-saving strategies, which have been proven to reduce energy consumption by half (see Figure 2-1). Many energy-efficient measures can be readily adapted in buildings, and even small actions, such as switching to energy-efficient lighting, can contribute to a considerable reduction in energy usage.

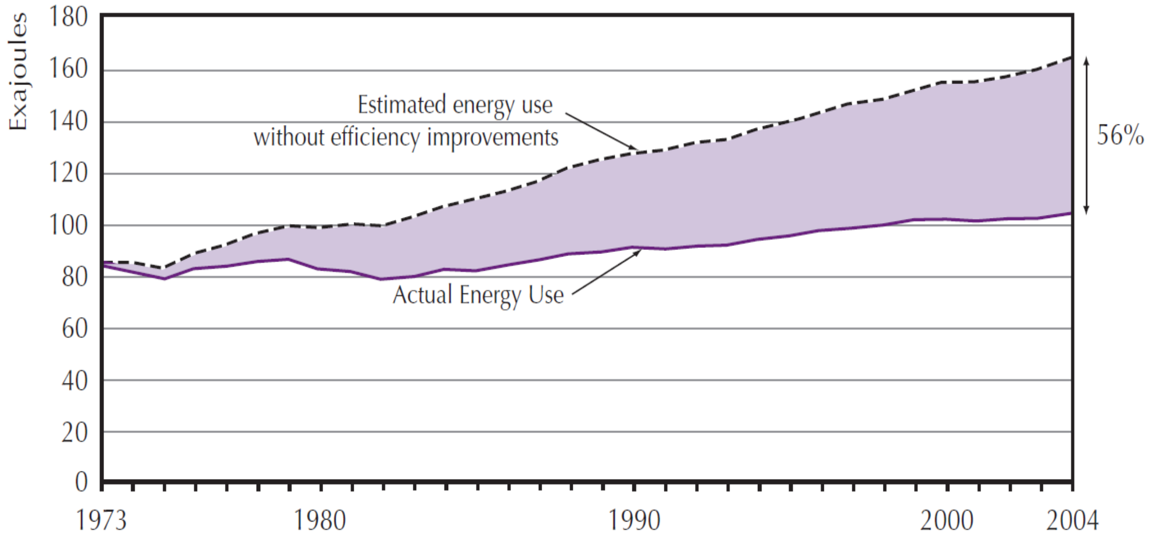


Figure 2-1 Energy savings since 1973 with energy-efficient measures (IEA, 2008)

Other practices that could similarly contribute to a reduction in energy and that could be accomplished without difficulty include the use of energy-efficient windows, the purchase of energy-efficient appliances and the application of an insulation layer around the building fabric (Kubba, 2010).

There are a number of factors that affect energy use in a building (see Figure 2-2); these could be attributed mainly to the building envelope, its systems, the specific external climate and occupants' behaviour. The process of using less energy would be possible by collectively considering the different contributing factors during the preliminary design stage, construction and useful life of the building (CIBSE, 2012).

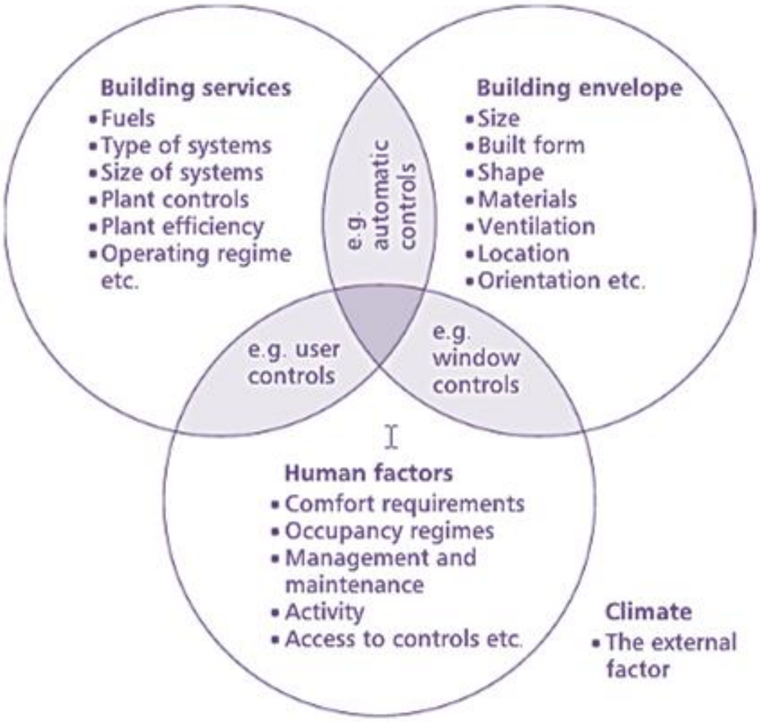


Figure 2-2 Factors that affect energy consumption (CIBSE, 2012)

During the end of the 20th century and the beginning of the 21st century, a large economic/energy debate was related to implementing energy-efficient measures. Many papers were published that studied the effects of energy-efficient measures on the built environment and its role in mitigating greenhouse emissions (Allouhi et al., 2015; Brown, 2015; Wada et al., 2012). However, a number of studies were sceptical of the rebound effect of reducing energy costs in respect to increasing energy use (Brookes, 2000; Brookes, 2004; Greening, Greene and Difiglio, 2000). Nevertheless, energy-efficient measures have been proven to reduce energy use through the numerous parametric studies related to the different possible energy-efficient measures in buildings (Bhattacharjee et al., 2014; Ruparathna, Hewage and Sadiq, 2016; Stephan, Crawford and de Myttenaere, 2011).

Governments, research groups and other voluntary agencies have developed codes and standards that aid end users to measure and moderate energy use in the built environment. Regulating approaches could fall either under mandatory building codes/regulations or voluntary standards or certifications (Allouhi et al., 2015; Bartlett, Halverson and Shankle, 2003; Casals, 2006). Most resources refer to two main approaches for the regulating codes

– either a prescriptive-based or thermal performance-based code. However, VanGeem mentioned a third approach, which she referred to as a hybrid approach, which is an outcome-based code (VanGeem, 2014).

Prescriptive codes may be denoted as thermal envelope codes, which normally would outline specific requirements for the fabrication of the outer envelope to regulate the energy use of a building. This normally includes a specific range of thermal transmittances (U-values) for the walls, floor and roof. A similar requirement for the glazed surfaces may be outlined along with or in place of a glazed to opaque surface ratio. Additionally, a description of the heating and cooling system and renewables may be included in the regulation (IEA, 2013b; Laustsen, 2008). Performance codes could be seen as the evolving form of the prescriptive codes. In contrast to the envelope code, the performance codes include a holistic energy performance with a full calculation methodology, a possible energy certification and an HVAC inspection. This, in turn, requires a higher level of expertise and training, but can ensure a better understanding of how the building may perform (Allouhi et al., 2015; VanGeem, 2014).

The first performance-based building code can be traced back to the 19th century BC, when King Hammurabi set the much known Hammurabi code, containing over 200 laws. Building performance regulations were found in article 229, where requirements for durable and safe buildings were stated in the law (Foliente, 2000).

The outcome-based approach, in addition to setting out a target for energy use, encompasses a post-measurement step to acquire the actual energy use in the buildings. This approach enables end users to be more aware of the actual energy being used, instead of the predictions made based on a simulated model of the building. The benefits of this approach also eliminate any possible errors that may have been encountered during the design and construction of the building (Colker, 2016).

In addition to the three approaches mentioned above, there are three more possible building codes – trade-off codes, model building and energy frame code target (Laustsen, 2008). The trade-off codes are close to the prescriptive codes, in the sense that they prescribe specific requirements for the building fabric or systems, but they offer more flexibility if not all requirements are met. For instance, if a lower U-value for the outer fabric has been achieved then, in return, the cooling system requirement may be overlooked. The model building code incorporates the use of a building model and a set of requirements to be fulfilled. A model shape representing the actual building with the required criteria applied to it is calculated. The calculations obtained through the model building are then compared against the as-built building fabric and systems. The outcomes should be found similar to or less than the model, giving more flexibility to achieving the overall energy target. Finally, the energy frame code comprises the calculation of the total energy loss in a building. This could be obtained, for example, by setting an adjusted U-value for the building per square metre of floor area. More freedom is granted again as the designer or contractor could achieve higher energy efficiency in one area and a lower performance in another while keeping within the same frame code target (Laustsen, 2008).

Building certification can be either voluntary or mandatory, although mandatory certification is claimed to be more successful, as it fully achieves its set targets (Casals, 2006). Different certifications provide different approaches, frameworks and methodologies, but all have the same target of achieving energy efficiency. Low energy buildings, zero energy or zero carbon buildings, passive house or positive energy buildings are the main outcome of these building certification labelling systems. The most well-known certification schemes include the Building Research Establishment Environmental Assessment Methodology (BREEAM), Leadership in Energy and Environmental Design (LEED) and Green Star (Allouhi et al., 2015).

Labelling systems or certifications go beyond building codes in terms of being able to deliver even better energy-efficient buildings, and could fall, to some extent, within the scope of outcome codes specified by VanGeem (2014). A holistic approach is provided through certification, not only covering the building fabric and systems but also extending further to include the life cycle of building materials, surrounding environment, and costs (Horvat and Fazio, 2005). Building performance certifications, in contrast to building codes, also offer the possibility of achieving variable classes within the same certification. For instance, a higher grade or class could be given to a building based on the amount of energy-efficient measures applied (Pérez-Lombard et al., 2009).

A number of studies in the past few years have been dedicated to producing a comparative analysis between the most widely used schemes (Lee, 2012). LEED and BREEAM were found to be the two most well-known and globally used schemes. They have been compared alongside other rating schemes from different parts of the world (Lee, 2013; Nguyen and Altan, 2011; Sharifi and Murayama, 2013).

Certification, even though it may be conceived as a more complex and demanding task in comparison to building code outcomes, can result in a higher-performing building (Casals, 2006). With certification, a possible recertification could be issued for a building three to five years after occupancy (Lee, 2013). This ensures that the building performance is being carefully monitored and updated as the building ages.

"Energy rating of a dwelling can provide specific information on the energy consumption and the relative energy efficiency of the building" (Santamouris, 2005, pg. ix). Standards and rating systems are becoming an integral part of the built environment. With the widespread alarms of climate change, and the quest to reduce the demand for fossil fuel, many countries are on a mission to adopt or upgrade building standards and assessment tools. However, the path towards achieving energy efficiency will not be realised without the regulating codes and rating systems. The assessment of buildings and even comparison between one and another will not be achievable without the rating systems. Standards and rating systems should, therefore, ensure a better-maintained and performing building stock in the future. The implementation of building standards and codes goes beyond ensuring that a certain level of efficiency is achieved in the building stock. Its importance will even address the reliability of buildings to withstand future demands; it eventually would lead to an automated mitigation policy for the building sector.

2.3 Climate Change and Energy Efficiency

Man-made interventions have been identified as one of the main contributors to greenhouse gas (GHG) emissions, which are directly linked to the causes of global warming (IPCC, 2015; Jentsch, Bahaj and James, 2008). Although climate change impact cannot be eliminated at this stage, measures and polices are being carefully studied and undertaken for adaptation or mitigation plans. The building stock is said to be of high potential to reduce GHG emissions, as much energy is utilised within this sector (IEA, 2013b). Additionally, buildings, unlike systems or appliances, have a long lifespan which may last for more than 50 years. The temperature changes expected through climate change are likely to overburden the building systems in the future. This, in turn, would be associated with accelerated energy consumption in the built environment (Li, Yang and Lam, 2012). Hence, it would be best to plan buildings today to be prepared for the changes of the future.

The Intergovernmental Panel on Climate Change (IPCC) was established as a regulating body that enables access to recent and reliable information about climate change. Reports and technical data are provided through the IPCC to assess the impact of climate change, not only on energy and the built environment, but also on different domains such as food, water and shelter (IPCC, 2015; National Research Council, 2010). The future has been illustrated by the IPCC through a number of storylines or paths, each presenting a possible alternative for how the future may unfold. Since its establishment, the IPCC has periodically revised its future scenarios to provide more reliable paths to the future. Three sets of scenarios have been announced to date, with the last being declared in 2014 in the latest IPCC report (Wayne, 2015).

The scenarios are based on current and past observations of certain indices, such as changes in the atmospheric composition, demographics and socio-economic development (IPCC, 2015; Nakicenovic and Swart, 2000). Using a common set of scenarios provides a unified basis for all scientists and researchers when studying the impact of climate change and producing mitigation and adaptation policies (Nakicenovic and Swart, 2000). The first set of scenarios (IS92) was released in 1996, followed by the second set (SRES) in 2007, with the most recent set announced in 2014 (RCP) (van Vuuren et al., 2011). The scenarios vary in their degree of severity, from mild to extreme, for possible predictions of how the future may look.

The SRES scenarios are composed of four family sets (A1, A2, B1, and B2). Each scenario is broken into a number of possible storylines, reaching 40 possible future outcomes. The scenarios include a wide range of possible growth patterns covering economic growth, demographic growth, and technological advances and emissions levels (Bernstein et al., 2008). The A1 scenarios represent a growing global world economy and population that peaks and later on declines at mid-century. The A1 category is characterised by utilising advanced technology and energy-efficient measures, and covers a wide range of CO_2 emissions. The A2 family represents a more diverse world, where less collaboration is attained across nations. Economic growth is fragmented between different nations and technology is not utilised to its fullest. Additionally, in this scenario, population growth is expected to be the highest among the different storylines, and CO_2 emissions are expected to continuously increase throughout the century. The B1 storyline represents a similar approach to the A1 scenario where a global economic and demographic growth is anticipated which peaks and declines afterward. However, more sustainable measures are associated with the B1 scenario as advanced technology and systems are utilised around the world. Finally, similar to the B1 scenario, the B2 scenario predicts a sustainable world, but at a lower and less global pace, and a faster declination of CO_2 emissions. In addition, an intermediate population and economic growth is predicted. The economic and sustainable solutions in this category are considered to be local or regional compared to the A1 and B1 scenarios (Nakicenovic and Swart, 2000).

The recent sets of scenarios (RCP) are based on the Representative Concentration Pathway of GHG concentrations, unlike the SRES scenarios, which were based on socio-economic narratives (Wayne, 2015). Four RCPs were developed, leading to radiative forcing levels of 8.5, 6, 4.5 and 2.6 W/m^2. A low forcing RCP 2.6 is associated with a mitigation policy, two medium stabilisation scenarios, RCP 4.5 and RCP 6, and a high forcing RCP8.5 emission scenario (van Vuuren et al., 2011).

"Considering the effects of climate change, building practices will have to change to ensure buildings continue to fulfil their functions throughout their life cycle." (Iannaccone, Imperadori and Masera, 2014, pg. 75). Many studies today address the topic of climate change impact on the built environment, with the main focus on thermal comfort and energy use (Holmes and Hacker, 2007; Karimpour et al., 2015; Li et al., 2015; Roetzel and Tsangrassoulis, 2012; Taseska, Markovska and Callaway, 2012; Yau and Hasbi, 2013).

Yau and Hasbi (2013) put together a comprehensive review on the impact of climate change on energy use in commercial buildings. The study covered the projected energy use, peak demands, cooling and heating demands, CO_2 emissions and sustainability in buildings, more precisely in buildings using active cooling systems. The outcomes showed that all the reviewed studies indicated an increased energy use due to the temperature rise. In addition, buildings subject to severe weather conditions were potentially at higher risk of deterioration, increased indoor pollutants and discomfort. Buildings, particularly in the tropics, are subject to extreme future weather events, and very few studies have adequately addressed the matter. Therefore, further studies and mitigation plans were suggested through careful consideration of the built environment for the specific region (Yau and Hasbi, 2013).

Another study carried out by Holmes and Hacker in 2007 focused on the thermal comfort of free-running buildings. Their study showcased the future performance of a number of low energy buildings in the UK. A reference to a study carried out by The Chartered Institution of Building Services Engineers (CIBSE) was highlighted in the paper. The referenced study pointed out that good-quality low energy houses may provide a better resilience option for future climate change. In addition, the authors analysed a number of existing low energy buildings in the UK and how well they could cope with the future increased summer temperature. The outcomes indicated that constructing low energy or sustainable buildings may lead to a future-proof solution if four principles are applied: proper shading, proper distribution of internal gains, provision of ventilation, and cooling only when needed (Holmes and Hacker, 2007).

Karimpour et al. (2015) produced a study on climate change impact on building envelopes for domestic dwellings in Australia. Their study referred to a number of previous studies carried out in different parts of the world. The main focus of the cited studies was on the impact of climate change on cooling or heating demand based on building envelopes. The authors' research, on the other hand, demonstrated a parametric study to achieve a future-proof building envelope for the specific region. The findings indicated that the building envelope needed to be carefully designed for the future. Additional insulation, better glazing, radiation barriers and flooring materials were suggested for the specific case study.

Recommendations were added to further asses other parameters that were not included in the study, such as the window size, shading elements and building orientation (Karimpour et al., 2015).

Another study, which was carried out in the United States, examined the annual and peak demand of several commercial and residential buildings in the Eastern Interconnection grid area of the country. Dynamic simulations were used to measure the loads of the different buildings throughout a 100-year period (2000-2100). The study concluded that there were variable load demands across the different building sectors, building types within each sector and across the different states. Climate change along with the specific building types were the main factors in the change of the consumption patterns (Dirks et al., 2015).

The impact of climate change in the previously mentioned studies was mostly assessed through the use of a projected weather data set incorporating the IPCC future scenarios. Dynamic building simulation tools are typically used with an associated weather data file for the specific location and period to study the impact of climate change on the built environment (Guan, 2009). Present-day weather files are readily available through the web from different sources, such as the US Department of Energy EEER website, or can be generated using weather-generation tools such as Meteonorm (Jentsch, James and Bahaj, 2010). Future weather data, on the other hand, is not available normally for direct download from the web and has to be generated (Cox et al., 2015). Guan (2009) pointed out four different approaches to generate future weather data. The extrapolating statistical method (degree-day method), the imposed offset method, the stochastic weather model and global climate models (Guan, 2009). Many of the later-mentioned methods have been implemented in a number of studies to generate future weather files for specific contexts (Cox et al., 2015; Ebrahimpour and Maerefat, 2010; Haase et al., 2010; Jentsch, Bahaj and James, 2008; Zang et al., 2013).

Cox et al. (2015) pointed out that increased attention has been given to the prediction of climate change impact on the built environment. The authors proposed a simplified weather file that deals with future heating and cooling demands in the built environment. The composition of the future weather file incorporates the sole effect of an increased dry bulb temperature parameter. Two methods were used to estimate the future heating and cooling loads, through the use of degree-day method and dynamic simulations. Three buildings with variable thermal properties were used for comparison purposes. The outcomes indicated that, even with a simplified future weather file, changes in energy demand are noticed – although the predictions may not provide a holistic approach for climate change impact, as only one variable is altered in the future weather set. The efforts exerted by the authors indicate the importance of assessing climate change and its impact on the built environment (Cox et al., 2015).

Haase et al. (2010) generated future weather data sets for Norway that would be compatible to use for building simulation tools. Three sets were generated, for 2020, 2050 and 2080. Morphing of the standard 1961-1999 weather files was carried out and two weather file sets were generated for use in the simulation tools – a Typical Meteorological Year (TMY) and an EnergyPlus Weather data file (EPW) file. The files used the IPCC models, and an A2 scenario (medium-high emissions) impact was selected for the morphed weather. Future comfort issues were the main driver for generating these future weather files for Norway. The authors found that the cooling degree days would increase in the next 100 years, causing a risk of overheating during the summer months, and even through spring and autumn. The authors concluded that buildings should be designed for the future by implementing more passive cooling techniques rather than merely focusing on strategies to reduce the heating demands (Haase et al., 2010).

Future weather files have been similarly developed in the UK by a number of organisations and research groups. The Chartered Institution of Building Services Engineers (CISBE) produced a number of weather files in different formats. The weather file sets are made available through direct download for use while simulating current and future performance of buildings (CISBE, 2015). Additionally, the Climatic Research Unit (CRU) at the University of East Anglia has produced climate change weather file sets for a number of locations in the UK. The Built EnvironmenT: Weather scenarios for investigation of Impacts and eXTremes (BETWIXT) project undertaken by the CRU in 2006 included the climate change impact on a number of weather parameters, such as temperature, precipitation and humidity, in addition to other parameters (CRU, 2006). The Sustainable Energy Research

Group (SERG) at the University of Southampton has also produced future weather files for the UK. Two of the most commonly used weather file formats were created, the Typical Meteorological Year (TMY) and an Energy Plus weather data file (EPW). SERG followed the methodology detailed by CIBSE to produce the future weather sets. As a result, a Microsoft Excel-based weather generator tool was produced. The weather generator operates by uploading standard current weather files approved by CIBSE to generate the future weather files through a morphing process. Additionally, a world weather generator was created by SERG which produces EPW and TMY files for any location around the world, provided that a valid EPW file is uploaded into the tool (Jentsch, Bahaj and James, 2008; SERG, 2015).

In developed countries, actions have already been undertaken to mitigate climate change risks by setting out targets to cut down GHG emissions. In 2008, the UK government set the world's first long-term emission-reduction target of 80% reduction by 2050, along with founding a separate committee on climate change (Gethering and Puckett, 2013). The EU Directorate-General for Climate Action has similarly set its 2020 climate and energy targets. These include a 20% reduction in GHG emissions, a 20% improvement in energy efficiency and 20% of EU energy coming from renewables (European Commission, 2015).

Developing countries, on the other hand, have shown a mixed energy policy. Countries in Africa, Latin America, the Middle East and Asia have just started to show progress in applying energy codes. However, they are still considered to be at an early stage in terms of climate change policies compared to developed countries. More developments in these areas are anticipated in the coming years (Iwaro and Mwasha, 2010).

2.4 Energy Performance Standards in the GCC

The Gulf Cooperation Council (GCC) (see Figure 2-3) was founded in 1981 with six founding member states, the Kingdom of Bahrain, the State of Kuwait, the Sultanate of Oman, the State of Qatar, the Kingdom of Saudi Arabia and the United Arab Emirates (UAE) (Al-Sahlawi, 1988).

Figure 2-3 GCC countries (Google Maps, 2016)

Oil and gas have been the main sources of energy in the GCC countries (Al-Mulali and Ozturk, 2014; Munawwar and Ghedira, 2014). Up until recent years very little attention was given to sustainability and green practices in the region. The abundance of non-renewable energy and very low tariff rates meant both governments and consumers were not very interested in joining the world in the sustainability race. However, with the booming development in the built environment and accelerated economic growth in the GCC, more attention has been given to addressing the issue of sustainability (Lahn and Preston, 2013; Meltzer, Hultman and Langley, 2014). Additionally, with the increased global awareness and the ratification of international treaties with a number of different international organisations, the GCC countries have started implementing green practices in the past few years.

Although the GCC countries are not considered the highest emitters of GHG emissions in absolute terms, several GCC states fall within the highest 10 GHG emitters in terms of emissions per capita (Meltzer, Hultman and Langley, 2014). In addition, all GCC countries fall within the highest CO_2 emitters per capita (World Bank, 2016a) – (see Figure 2-4). Most of the energy is exploited within the residential sector; almost 47% of the total energy is consumed in homes due to the huge economic and population growth in recent years (Al-Mulali and Ozturk, 2014).

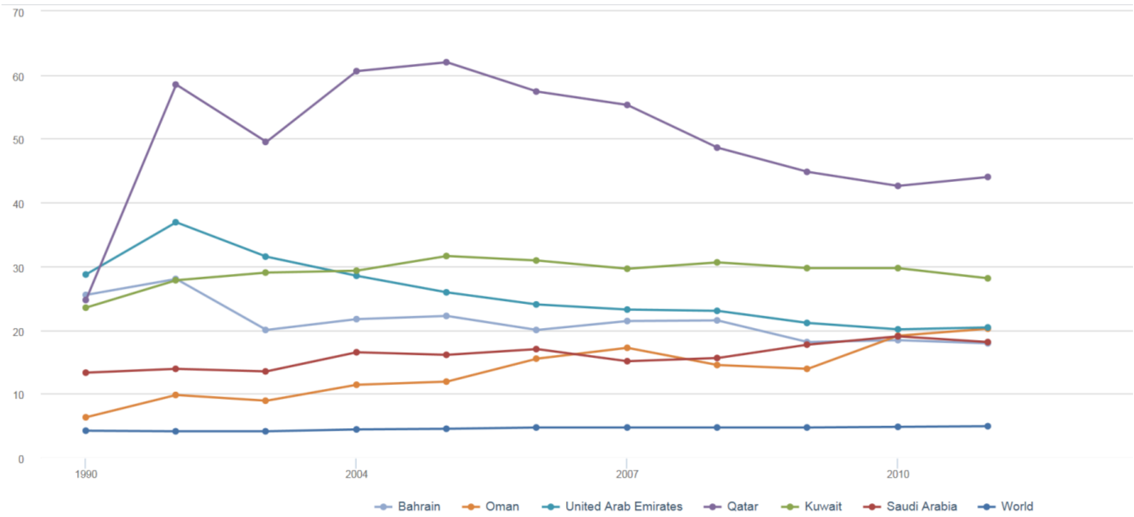


Figure 2-4 GCC CO_2 emissions (metric tons per capita) (World Bank, 2016a)

A number of studies and surveys have been undertaken in the GCC region during the past few years with the main concern of mitigating GHG emission and paving the way towards sustainability. A few studies targeted the assessment of the current codes and energy policies in the region (Awawdeh and Tweed, 2006; Iwaro and Mwasha, 2010; Radhi, 2009; Radhi and Sharples, 2009; Reiche, 2010), while others investigated the potential of renewables in the area (Bhutto et al., 2014; Doukas et al., 2006; Munawwar and Ghedira, 2014), and a few more studied the impact of climate change on the region (Alhorr and Elsarrag, 2015; Jentsch, James and Bahaj, 2010; Spiess, 2008). All studies pointed out that fossil fuels were the main source of energy and raised concerns with regard to the depletion of resources. Furthermore, sustainable measures were agreed to be the right path to concur at present to ensure a stable transition from a fossil fuel-dependent energy budget to a possible mixed renewables energy budget.

Thermal codes were used in the GCC as early as the 1980s (Awawdeh and Tweed, 2006) but, due to the rapid development of the building sector, building regulations were not followed strictly, or were not even obligatory in some cases (Willis, 2015). According to

Awawdeh and Tweed (2006), mandatory building envelope codes were applied largely to mechanically conditioned new buildings in the region. The regulations included maximum U-values set for both the roofs and walls for all state members. In addition, glazing-type restrictions laws were applied in some member states. The authors pointed out that more measures should be employed to conserve energy use in the region, including more consideration of glazed surfaces, efficient HVAC systems and lighting, in addition to applying the conventional passive design approaches such as proper shading and consideration of the building orientation (Awawdeh and Tweed, 2006).

After 2006, 'green' action began to spread in the Middle East, with green building councils starting to emerge in Arab cities in the UAE, Jordan, Qatar, Saudi Arabia, Egypt, Oman, Morocco, Kuwait and Syria (Willis, 2015). More recently, building regulations have been revised in a number of GCC countries. For example, Saudi Arabia, Kuwait and the UAE (Dubai) have re-issued their building regulations (see Table 2-1); in addition, Qatar and UAE (Abu Dhabi) have adopted assessment rating systems.

In 2007, new regulations were declared in Saudi Arabia with the announcement of the Saudi Building Code (SBC). The code included technical features and guidelines for both new and existing buildings, energy conservation criteria, and other safety and health requirements for a variety of building types (Saudi Building Code, 2015). The energy conservation section of the code included measures for achieving energy efficiency in buildings. This was illustrated through regulating the buildings' envelope parameters, mechanical, electrical, lighting and domestic water-heating systems. Residential and commercial buildings are similarly included in the code and specific thermal transmittance is assigned for each building component (roofs, walls and windows) based on the cooling degree days of the specific region (Alaidroos and Krarti, 2015).

Table 2-1 GCC revised building regulations (adapted from (Awawdeh and Tweed, 2006; Dubai Electricity and Water Authority, 2015; KAHRAMAA, 2016; MEW, 2015; MEW, 2014b; Saudi Building Code, 2015; Muscat Municipality , 1992))

Components	Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	UAE (Dubai)
Walls	0.75	0.227-0.568	0.741	0.568	0.53-0.7[1]	0.57

Building envelope U-values	Floors	-	0.58	-	-	-	Insulated[2]
	Roofs	0.6	0.15-0.397	0.57	0.437	0.31-0.42[3]	0.3
Glazing Systems (W/m^2K)	U-value	2-5.1	3.61-2.0	-	3.3-2.10	2.67	2.1-1.9
	Cooling system	-	Included	-	Included	Included	Included
	Hot water	-	-	-	-	Included	Included
	Lights	-	Included	-	-	Included	Included
Enforcement (yr.)		1999	2014	1992	2010	2007	2014
Remarks		Reissued in 2002	-	-	Reissued in 2012	-	Renewables included

1 reduced U-values are required for government buildings, in addition to all buildings that are to be built after 2017.
2 floor to be insulated 1m from the parameter of the building.
3 reduced U-values are required for government buildings, in addition to all buildings that are to be built after 2017.
4 other sections of the Saudi code (401-501) state the electrical and mechanical requirements of the buildings.

Kuwait, on the other hand, revised its energy conservation code of practice – which is applicable to residential, commercial, special and government buildings – in 2014. The code states specific requirements for building envelopes and cooling and lighting systems. The regulation is considered mandatory for all new buildings and new installations of HVAC units in existing buildings, although government buildings are required to adhere more strictly to this code. This includes all public buildings, offices, and educational facilities, religious and residential buildings owned by the government (MEW, 2014b; Alsayegh and Al-Ragom, 2015).

Bahrain has been applying its thermal envelope regulation since 1999 (Awawdeh and Tweed, 2006). The code was obligatory for all newly constructed, mechanically cooled buildings that are four storeys and above (MEW, 2015). More recently, Bahrain has taken a few measures to enhance the energy efficiency of new and existing buildings. These include applying the thermal envelope code to all buildings that require cooling. In addition, a new decree was announced recently to regulate the efficiency of small cooling units (BNA, 2015; MEW, 2014a).

In the case of Oman, mandatory building envelope regulations do not seem to be applicable in the country. Two studies recently conducted in Oman indicated that the building stock suffers from poorly performing building fabrics and that energy efficiency measures need to be sought (Al-Saadi, 2015; Sweetman et al., 2014). Despite that, Oman has taken a number of initiatives to promote energy policies in the country. These include founding the Omani Green Building Council in 2013 (OGBC, 2013) and renewable energy projects announced by the Public Authority for Electricity and Water (PAEW, 2016).

The United Arab Emirates (UAE) and Qatar are currently leading the way in approaches to sustainability, as rating systems have been introduced in both countries (Willis, 2015). The Estidama Pearl rating system in Abu Dhabi and the GSAC rating systems in Qatar came in to action in 2010 and 2012 respectively (GORD, 2016; Sabie, Pitts and Nicholls, 2014). The Estidama Pearl rating system was developed under the authority of the urban planning council in Abu Dhabi (Estidama, 2010). It followed the 2030 economic vision for the Emirates and, more precisely, the urban development master plan (Willis, 2015). The rating system revolves around four sustainability aspects: economy, environment, culture and social domains (Sabie, Pitts and Nicholls, 2014). One pearl (the lowest score) on the rating system is obligatory for the residential and commercial buildings category, while governmental buildings have to achieve a minimum of two pearls (Issa and Al Abbar, 2015). The rating system was analysed by Assaf and Nour (2015), whereby a comparative analysis was conducted using a dynamic simulation tool. Three building types were assessed – a residential villa, a multi-storey office building and a multi-storey residential block. Two models were created for each building type, with one following the minimum pearl rating system and the other following business-as-usual practices. The study focused on the impact of applying the rating system on energy and water use by 2020. The results indicated that a possible 31-38% reduction in energy use and 22%-36% in water use was achievable by implementing the minimum pearl rating scheme (Assaf and Nour, 2015).

Dubai, on the other hand, the commercial hub of the UAE, has enforced its green building regulation and specifications to all building types since 2014. Previously, the regulation was only mandatory for government buildings and optional for private projects. (Alarabiya, 2014). The energy effectiveness section of the regulation covers the building envelope, glazing, building systems including HVAC, lights and lifts, and the elimination or insulation of thermal bridges, and the insulation of pipes and ducting works. Renewables are included in the code and are required for external lighting when it exceeds the power density specified in the regulation. They are similarly required for solar water heating in residential villas and workers' residences. Additionally, renewables are optional for all buildings as standalone systems (Dubai Electricity and Water Authority, 2015; Dubai Municipality, 2015)

The Global Sustainability Assessment System GSAC in Qatar, which was formerly known as the Qatar Sustainability Assessment System (QSAS), was developed by the Gulf Organization for Research and Development (GORD) (Willis, 2015). The chairman of GORD indicated that the development of the GSAS assessment system involved the study of around 40 green codes from around the world (GORD, 2012). The GSAS sustainability system is based on eight main categories: water, energy, indoor environment, cultural and economic value, site, urban connectivity, material, and management and operations. Water and energy, though, are rated higher than the other elements due to the country's specific needs (Issa and Al Abbar, 2015). The GSAS rating system covers various types of classifications including different types of buildings (offices, mosques, villas, schools etc.), and light industry, neighbourhoods, operations and railways (GORD, 2012). The rating system was assessed in two studies, one focusing on Life Cycle Analysis (LCA), while the other mentioned the GSAS as a neighbourhood assessment tool without further assessment of the rating system itself (Omar Attallah et al., 2013; Sharifi and Murayama, 2013). Omar Attallah et al. (2013) conducted research to measure the effectiveness of the environmental aspect of the GSAS assessment system. The LCA measure was used to assess the performance of the GSAS rating system through a proposed evaluation methodology. A building under construction in Qatar was chosen as the medium to perform the LCA study in comparison to the GSAS rating system. The results indicated that the rating system in some cases under- or over-estimates the weight of some credits in the environment category. Further consideration of the environmental aspect of the rating system was suggested.

Both the Estidama rating system and the GSAS rating system have been created to be adapted not only by the originating country, but to be expanded to other countries in the

Middle East. According to GORD, a number of countries have already shown interest in applying the rating system. Kuwait has signed a memorandum of understanding to implement GSAS. Saudi Arabia has also shown interest in applying sustainable measures through the rating system (GORD, 2012; GORD, 2016).

2.5 Energy-Efficient Buildings, Technologies, and Techniques

Energy-efficient buildings have become a subject of interest to many architects and designers in the past decades. They have spread rapidly within Europe and developed parts of the world, with the main aim of reducing energy consumption and GHG emissions (Allouhi et al., 2015). Although energy-efficient buildings or high-performance buildings (HPBs) have been cited widely in literature (GhaffarianHoseini et al., 2013), defining the latter term, although it may seem straightforward initially, is actually said to be rather more difficult (Trubiano, 2013). An even harder task to accomplish would be to specifically define all technologies or standards that would result in achieving an energy-efficient building or HPB (Concerted Action EPBD, 2016; Li, Hong and Yan, 2014). In 2011, the Concerted Action under the Energy Performance Directive issued a report, which was based on a survey, to define HPBs and energy-efficient buildings in the EU. More than 20 terms were found to be associated with HPBs in the region. According to the report, three categories could be defined. The first refers to low energy consumption buildings, which included the majority of the terms surveyed. This included technologies such as low energy house, ultra-low energy house, zero energy houses, plus energy house, and six more terms. The second group comprised low emission buildings, such as zero carbon buildings, zero emission buildings and emission-free buildings. Finally, the third category incorporated green or sustainable buildings, which comprised green buildings, eco buildings and other similar building types (Erhorn and Erhorn-Kluttig, 2011).

Another recent study (Ionescu et al., 2015) examined the historical evolution of energy-efficient buildings, highlighting the most significant technologies. According to the study, the definition of an energy-efficient building or approach could be associated with the type of examined performance criteria. This included energy consumption aspects, emission-related aspects, economical aspects and the period of evaluation. It is therefore not an easy task to limit energy efficiency standards or to strictly group them within a single category, as in some cases the definition may overlap between a numbers of categories. Low energy buildings, ultra-low energy, zero energy buildings and plus energy buildings are amongst the widespread trends in the energy-efficient building stock. According to Kibert and Fard (2012), a global definition for low energy buildings is not attainable, as the approaches to low energy homes differ from one context to another.

A generic definition of low energy buildings was, however, referred to in the review by Ionescu et al. (2015). The authors defined low energy buildings as buildings that used less energy than a standard building would. Another classification of energy-efficient buildings was demonstrated by Hernandez and Kenny (2010). The amount of annual energy and embedded energy buildings tended to use were used for the classification purposes with reference to generic building types (Hernandez and Kenny, 2010) – (see Figure 2-5).

Zero energy buildings (ZEBs), similar to energy-efficient buildings and low energy buildings, were found to be difficult to define (Stutterecker and Blümel, 2012). Many versions of ZEBs are found in the literature, either related to the renewable energy source, life cycle or energy balance (Li, Yang and Lam, 2013).

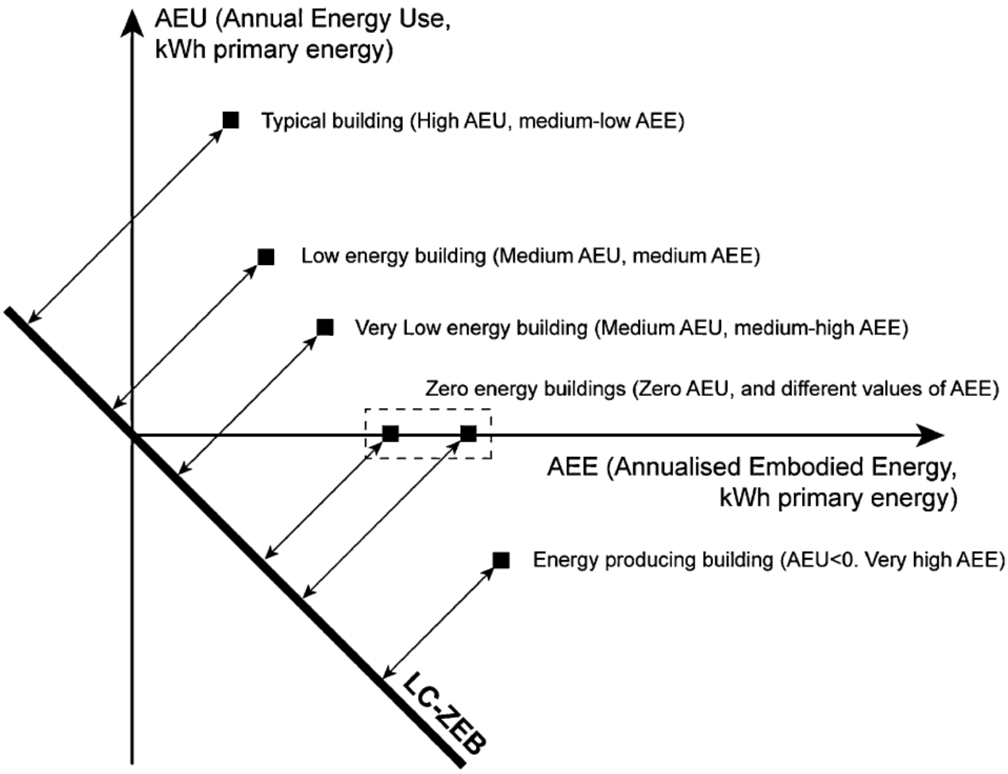


Figure 2-5 Annualised life cycle energy of some generic buildings (Hernandez and Kenny, 2010)

The trend to adopt ZEB technologies in the building stock is becoming more evident, and many developed countries have set targets towards achieving ZEBs in the next few years (Kibert and Fard, 2012). Plus energy buildings could be generically defined as buildings that produce an excess amount of energy through renewables as opposed to the amount of energy they receive from an external source (GBPN, 2013). Net zero energy buildings (NZEBs) have been associated in the literature with positive or plus energy buildings, as both are seen to be the future for buildings and the latter could occur through the evolution of the first (Ionescu et al., 2015).

Another energy-efficient measure that has gained an increased level of interest in Europe is the Passivhaus (PH) approach (Hopfe and McLeod, 2015; Ionescu et al., 2015; Hines, 2014). A number of Northern European countries have set their long-term goals to include Passivhaus certification as a voluntary or even mandatory requirement in the built environment (Mlecnik, Kaan and Hodgson, 2008). An increasing interest in the Passivhaus approach (PH) can also be traced to the United States, where independent research and certification is carried out under the Passive House institute in the US (PHIUS, 2015).

In the literature, a number of researchers have also linked the two widespread approaches together, the ZEB and PH buildings. The justification behind this link refers to the fact that a zero energy house needs to be constructed in a highly energy-efficient manner, which was found to be promptly addressed in the PH standard (Carlucci, Zangheri and Pagliano, 2013; Hopfe and McLeod, 2015).

The previously mentioned technologies provided the means towards achieving energy efficiency in the built environment. While it proved difficult to provide exact definitions, as contextual differences imposed different approaches, research was directed towards identifying the practices or techniques that led to achieving energy-efficient buildings (GhaffarianHoseini et al., 2013; Ionescu et al., 2015; Li, Hong and Yan, 2014; Li, Yang and Lam, 2013). Techniques that lead to achieving an energy-efficient building are versatile and are also highly dependent on the climatic context and specific region's construction methods and expertise.

A basic approach has been illustrated by Li, Yang and Lam (2013). This included defining three categories that affect energy consumption in a building. The first category includes the building envelope, which is composed of thermal mass, thermal insulation, glazing and green and reflective roofs. The second category comprises the internal conditions, which include indoor thermal comfort and internal heat loads. The final category covers the building systems, which consist of heating/cooling systems, ventilation systems and other systems such as lights and lifts (Li, Yang and Lam, 2013). According to the IEA's energy efficiency requirements for building codes and energy efficiency policies for new buildings (Laustsen, 2008), energy could be reduced through addressing a number of parameters. This includes the following considerations:

- Building envelope, providing a proper articulation of the outer fabric, in addition to addressing floors, walls, windows and roofs. Reduction of infiltration rates and implementation of different shading systems.

- Efficient heating, cooling and ventilation systems, in addition to other systems, such as water heating, dehumidification, the associated ducting and piping work, should be carried out efficiently to avoid air leakage.
- Implementation of renewable energy, including passive solar techniques, passive cooling and other renewable systems.
- Improved efficiency of electrical equipment and appliances, such as highly efficient lighting and energy-labelled small power equipment.

A recent comprehensive review conducted by De Boeck, et al. (2015) examined the improvement of energy-efficient measures in the residential sector. The study analysed 78 studies that targeted energy efficiency within domestic homes in different parts of the world. Based on the dwellings examined in these studies, De Boeck et al. concluded that the targets for improvement could be listed under five main categories:

- The building's outer fabric, which included the roof, floor and wall insulation thickness and material type.
- The building's heating/cooling and ventilating systems, in addition to other systems such as solar systems, and other renewables.
- The building's glazing and shading systems, with the focus on glazing type and size and external shading.
- The building's other appliances and lighting.
- The whole building, which included the building shape, orientation, thermal mass and infiltration levels.

Harvey (2013) agreed with both De Boeck and the IEA report. In his research, he examined the energy and economic impacts of different technologies applied to the built environment around the globe. Harvey highlighted the basics of achieving a low energy building, which included the following approaches:

- Optimising the building's form, orientation and thermal mass.
- Articulating a high-performance thermal envelope.
- Implementing passive techniques, such as passive cooling, passive heating and ventilation in addition to maximising daylighting.

- The remaining loads should be met by energy-efficient systems, such as energy-efficient heating/cooling or ventilating and dehumidification systems.
- Utilising energy-efficient appliances and lighting.
- Finally, ensuring that the whole building and its systems are cost effective.

2.6 Summary

Energy efficiency in the built environment has become a subject of interest to many architects and engineers. Energy efficiency not only moderates energy use, but also mitigates GHG emissions and ensures better indoor thermal comfort. Numerous studies have been carried out by researchers around the world to assess energy-efficient measures through parametric and post-occupancy studies (Dakwale, Ralegaonkar and Mandavgane, 2011; Mahdavi and Doppelbauer, 2010). Other research is directed towards establishing a framework to pave the way towards the sustainability of energy-efficient building and the measurement of how efficient a building is (Lee, 2012; Nguyen and Altan, 2011; Pérez-Lombard et al., 2009). Energy efficiency has also been found to be an effective mitigation policy to address climate change. The IEA reports have pointed out that buildings are responsible for one-third of the world's energy consumption in addition to CO_2 emissions. Buildings are therefore of high potential to reduce energy use through efficient measures. A recent IEA energy outlook has even indicated that one-third of the global energy demand could be reduced through implementing energy efficiency measures in the built environment by 2040 (IEA, 2013b).

Energy efficiency measures have also been sought in the GCC; a brief overview has been presented highlighting the most recent updates in the area. The importance of addressing the current energy situation in the GCC is directly related to the context of this research. Qatar, a member of the GCC, has recently launched an experimental ultra-low energy house, which is the subject of this research (Bryant et al., 2013). A clear understanding of the energy balance in the area would identify the need for applying energy-efficient measures. It would also allow the opportunity to further assess the feasibility of applying energy-efficient technologies that have gained acceptance in different parts of the world. Finally, energy-efficient technologies were discussed, citing those most commonly adopted in developed countries. Obtaining a clear definition for energy-efficient typologies was found to be a daunting task; therefore, generic approaches were illustrated for each. Through the literature review, it was found that a holistic approach to achieving energy-efficient buildings is attainable. A number of comprehensive studies have been carried out that addressed the subject of achieving energy-efficient buildings through energy reduction (Grin, 2008; Housez, Pont and Mahdavi, 2014; Parker, 2009). The examined studies indicated that energy efficiency could be achieved through optimising the building envelope and its systems. Additionally, technological advances in both materials and renewable energy could contribute to upgrading the building to a higher level of energy efficiency (IEA, 2013b).

The next chapter will shed light on one of the fastest-growing energy-efficient standards – the Passivhaus standard. More than 50,000 buildings have been built around the world following this standard, although most of them have been constructed in Europe (Lewis, 2014).

Chapter Three
The Passivhaus Standard

3 The Passivhaus Standard

3.1 Overview

The Passivhaus (PH) standard initially evolved in Germany 25 years ago. It first emerged as a construction principle applied to residential buildings (Passepedia, 2015). The term Passivhaus in German refers to a passive house or building, and some references might use the English translated version “Passive House”. This, to a certain extent, has caused a degree of confusion with the well-known passive solar design approach in architectural design (Cotterell and Dadeby, 2012). In this research, the German term Passivhaus (PH) will be used to avoid any possible misperception. Although the Passivhaus approach permits the use of mechanical cooling/heating, with certain limitations, passive design techniques are encouraged based on the specific climate context to reduce energy use whenever possible. Therefore, full utilisation of solar heat is applied in order to warm living spaces, and night ventilation is encouraged similarly, whenever applicable, to cool the air temperature during the night (CEPHEUS, 2001). Additionally, a significant insulation layer and shading systems are applied, along with other passive techniques, with the aim of lessening the load on the mechanical systems and, ultimately, energy consumption. The current chapter will discuss the evolution and definition of the PH standard and its criteria. Finally, a number of studies will be presented from Europe and around the world to demonstrate the spread and success of the standard.

3.2 The Passivhaus Definition and Historical Background

The official definition of the Passivhaus, according the Passivhaus resource web page, is “*A Passive House is a building for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air”* (Passepedia, 2015) (see Figure 3-1).

Other definitions of the PH have also been found in the literature. According to Lewis (2014, pg. 8), *“A Passivhaus is a very well insulated and draught free building designed to provide* *the highest level of comfort*". Cotterell and Dadeby (2012) agreed in essence with the previous definitions. According to them, *"A Passivhaus building is designed to be very comfortable and healthy, and to use vastly less energy than conventional buildings, irrespective of the climate"* (Cotterell and Dadeby, 2012, pg.17).

Similarly, Trubiano referred to the PH as an easily adaptable low energy standard that could be applied to any building in any location. The secret of the PH standard, according to Trubiano, rests in the highly sealed insulated outer fabric and effective heat recovery system. Trubiano views the PH as a prospect to achieve both high performance and high-quality architecture at the same time (Trubiano, 2013).

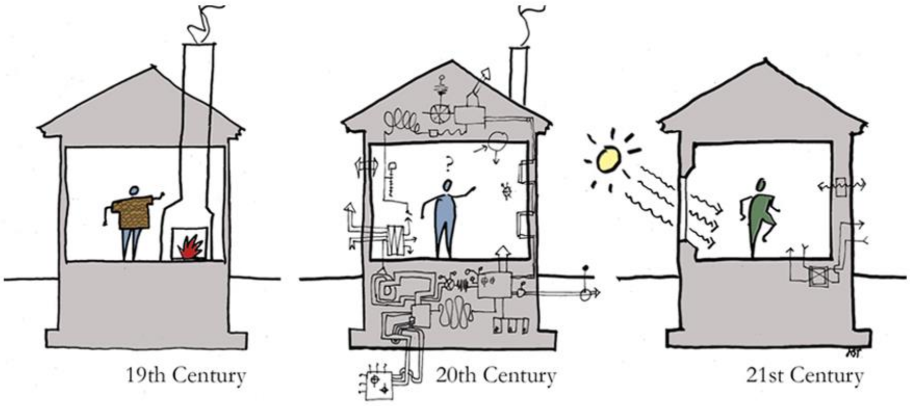


Figure 3-1 Passivhaus approach transition for the 21st Century (A R T Architects, 2016)

The first recognised building that applied the Passivhaus techniques was the Darmstadt house in Germany in 1991. A few years later, the Passivhaus Institute (PHI), which is the main organising body responsible for developing and regulating certifications for the standard, was founded in 1996 in the same city by Wolfgang Feist (Trubiano, 2013). Since then, almost 50,000 Passivhaus buildings have been built around the world, mostly within Europe (Lewis, 2014).

The concept of the Passivhaus is not new, as since olden times people have strived to create better living conditions in their homes, although in those days energy consumption was not the main driver. In addition, technologies and advanced materials were not available. People had to use their instinct and available resources to survive severe weather. The balanced temperature of the earth provided shelter from extreme weather: houses in

Tunisia and in the Carpathians were partially buried underground to achieve thermal comfort. Many other examples can be cited from different parts of the world, such as using mud and straw as insulating material in the vernacular architecture of many countries. The use of wind-catchers in the Middle East brought cool air into buildings and utilised evaporative cooling in the design to achieve a better indoor environment (Baker and Steemers, 1999; Ionescu et al., 2015).

Primitive solutions, in addition to many experimental houses in the 1970s and 1980s, have led to the formation of the PH standard as it is known today (Passepedia, 2015). A building that significantly influenced the PH development was the DTH zero energy house built in 1973 by Professor Vagn Korsgaard at the Technical University of Denmark. The house was built with a super-insulated envelope, low infiltration level and a heat recovery in the ventilation system, and it was a very low energy building at that time (Esbensen and Korsgaard, 1977).

The Saskatchewan Conservation House built in 1977 in North America represented the benefits of superinsulation and embodied an example of an early PH through its insulated walls, solar heating and low energy consumption (Besant, Dumont and Schoenau, 1979). In fact, the original idea of the Passivhaus was formulated following a visit to China. Professor Bo Adamson from Lund University, Sweden, was assigned to design buildings that required passive heating in the southern part of China during winter. The resultant buildings were named Passive Houses and triggered the implementation of the concept in Europe (Müller and Berker, 2013).

The PH standard was later introduced in 1988 as a collaborative effort between Dr Wolfgang Feist and Professor Bo Adamson. Five main pillars were to be incorporated in the PH design: an airtight, highly insulated envelope, with minimum thermal bridges, and well-insulated windows, and a heat-recovery ventilation system (Trubiano, 2013). The construction of the Darmstadt house shortly followed the declaration of the standard in 1991. The house was experimental in nature and was constructed under the supervision of a scientific research group. Prior to the actual execution of the house, the research team carried out a thorough investigation to develop bespoke building components and designs for the project. The building components incorporated the fabrication of new window frames and an efficient ventilation system and associated controllers. In addition to that, the design of new building details for thermal bridges, and improved architectural detailing and drawings were undertaken. The research also involved the development of a new solar water-heating technique and heat recovery from the waste water. As a result, four terraced houses were built incorporating the new building components and details. In addition, the houses were extensively insulated with around 250-450 mm of insulation layer around the walls, roof and basement. Upon completion, the houses were occupied and monitored. The results reported the verification of the PH theory and the possible achievement of a reduction in energy through the implementation of the five pillars. As of 2010 the houses were still occupied by the same families and the heating loads remained on average around 10 Kwh/m^{2}a, with an 80% reduction in energy consumption (Passepedia, 2015; Trubiano, 2013).

Associated with the PH standard is the Passive House Planning Package (PHPP), which was first introduced in 1998. The PHPP is a Microsoft Excel-based calculation tool developed by the Passivhaus Institute (PHI) and primarily used in the PH certification process. According to Cotterell and Dadeby, the use of an Excel-based tool can be mainly related to the PHI's desire to disclose the calculation procedure carried out in PHPP to the users, and is also partially due to financial commercial reasons (Cotterell and Dadeby, 2012). The calculation tool has been verified and tested against a vast number of Passivhaus buildings and is said to provide highly accurate results (Müller and Berker, 2013). According to the PHI, the results obtained from the PHPP are highly reliable. This includes outcomes of cooling and heating loads, summer comfort percentages in passively cooled buildings, and the primary energy and renewable energy demands (PHI, 2015e). The PHPP is designed to include a number of worksheets through which the user is guided via colour-coded cells. Whenever data are required, the cell will be accessible and highlighted in yellow. Result cells and reference cells are highlighted in white and green respectively. Based on the input data, embedded calculations are carried out to measure the energy performance of the building and present the results in the corresponding cells in comparison to the PH requirements (Cotterell and Dadeby, 2012).

The latest version of PHPP, “PHPP 9”, was released in September 2015. The PHPP, similar to the PH standard, has undergone different stages of improvements, which is evident through the number of released versions since 1998. The most recent version has been introduced in the latest Microsoft Excel format; in addition, it has extra and amended worksheets and additional separate Excel files. The new release incorporates the new PH classes, introduced alongside the recent PHPP version, as well as developing a 3D plugin for Sketch up, ”designPH”, acting as a complementary 3D interface for PHPP (designPH, 2015; iPHA, 2015; Passepedia, 2015; PHI, 2015e).

3.3 Passivhaus Criteria and Requirements

The key to the success of the Passivhaus standard lies in its highly articulated outer fabric and effective heat recovery system. The existence of a clear and specified set of guidelines to follow has further encouraged the adoption of the standard in buildings around the world. According to the Passivhaus Institute (PHI), five main principles should be applied when constructing a Passivhaus building (see Figure 3-2).

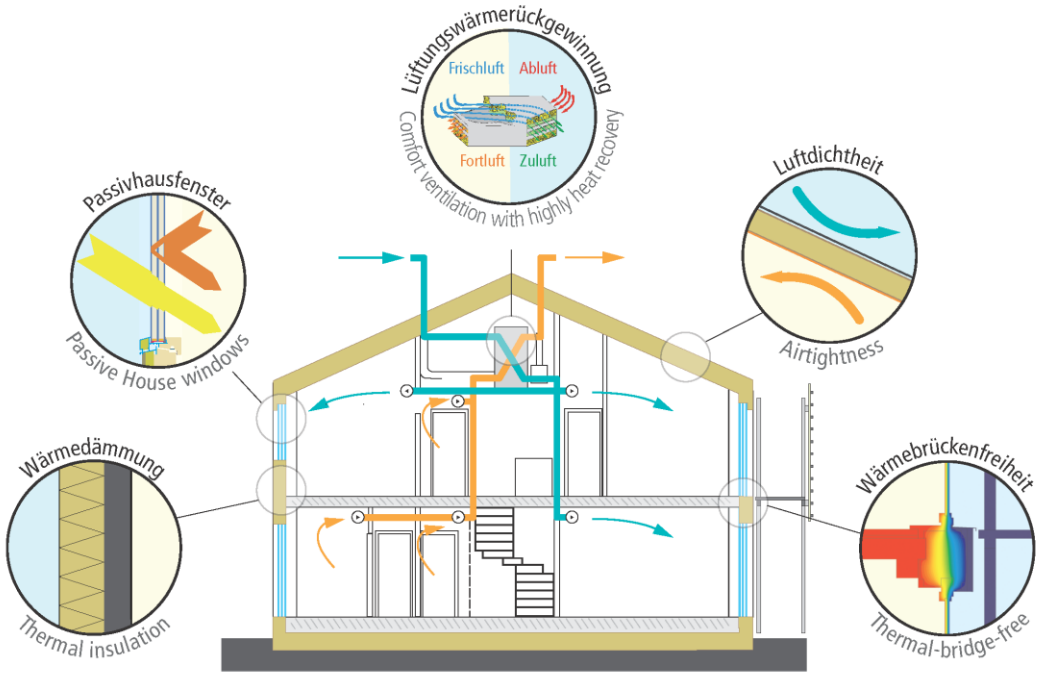


Figure 3-2 The five basic principles of the Passivhaus standard (Passepedia, 2015)

a. **Thermal insulation**: a key characteristic of a PH building is a continuous layer of insulation material covering the whole building envelope. This includes walls, roof and floors. A required minimum U-value for opaque surfaces is 0.15 W/m^{2}K for cool temperate climates (PHI, 2015d; Passepedia, 2015). The U-value is an indicator of the thermal transmittance of the building elements. The lower a U-value, the better the building elements are in keeping heat in or out of a building. U-values are also used for glazed surfaces, and are used to define the heat loss through the window frame, glazing and whole window respectively, normally differentiated through the symbols U_f, U_g and U_w (Cotterell and Dadeby, 2012).
b. **Passivhaus windows**: high-definition glazing and well-insulated frames are required by the PHI. Window U-values of 0.8 W/m^{2}K or less are required for cool temperate climates (PHI, 2015d, Passepedia, 2015). According to Lewis, the design of a PH building should incorporate the full potential of windows. This is achieved by locating and sizing windows to benefit from heat gain in the winter and lessen overheating in the summer. In addition to using U-values to measure the heat loss from windows, total solar transmittances or g-values are used in the PHPP to measure the amount of solar heat entering the building through the window. To achieve heat gains in winter and avoid overheating in summer, windows should have low U-values and high g-values (typically around 50%). In addition, there must be careful detailing around the windows (Lewis, 2014).
c. **Ventilation heat recovery**: a PH building must have an effective heat-recovery system with at least 75% of the heat extracted from the exhaust air and utilised to heat the fresh air through a heat exchanger (PHI, 2015d). The PH strategy is based on providing comfortable interiors. To obtain good interiors, fresh air must be allowed to circulate through the building, either naturally by operating windows or mechanically through a ventilation system. A popular misconception is that occupants are not allowed to open windows in a PH. In fact, according to Cotterell and Dadeby (2012), the PHI requires at least one operable window in each room. In addition, when the outdoor conditions are pleasant, natural ventilation is recommended during the day and even in the night. The idea behind using a mechanical ventilation system is based upon the fact that opening a window during

cold weather is not practical. The use of a ventilation system therefore ensures that fresh air is continuously drawn into the building to maintain indoor comfort. A ventilation system fundamentally extracts moist air from wet rooms in a building (toilets, kitchens, laundry room) to the outside and then provides clean fresh air from the outside to the inhabited rooms of the building (bedrooms, living rooms, study); in this process, the two air streams are strictly separated. The incoming air is preheated by exchanging heat with the exhausted air, partially contributing to heating the liveable spaces (Cotterell and Dadeby, 2012).

d. **Airtightness**: there must be an airtight envelope that permits no more than 0.6 air changes per hour through the possible gaps within a building when an air pressure test is performed at 50 Pascals (PHI, 2015d). To visualise the amount of air changes acceptable in a PH, an area smaller than a 5p coin can represent the minimum leakage area for every 5m^2 of the building envelope. Achieving the designated airtightness level not only reduces energy use, but also ensures a better indoor environment. It also prolongs the lifespan of the building fabric and insulation through the reduction of moisture vapor. An airtightness test is carried out by what is known as a blower door test. Once the envelope is airtight, the test can be performed by placing a large calibrated fan in an airtight door or window panel. A digital pressure devise is used to measure the airtightness of the envelope. The test includes both depressurising and pressurising of the indoor air, thereby allowing the differences between the outdoor and indoor pressure to measure the air leakage levels (Cotterell and Dadeby, 2012).

e. **Absence of thermal bridges**: all corners, joints and connections must be handled with care to minimise any possible thermal bridges (PHI, 2015d). Thermal bridges normally occur when two building components are joined, such as walls meeting floors. It could also occur when different building fabrics come into contact, such as wood studs penetrating an insulation layer. The difference between the conductivity of materials penetrating an insulation layer is the main reason for thermal bridges. A thermal bridge-free building can normally be achieved through careful joint detailing and a continuous and uninterrupted layer of insulation (Lewis, 2014).

In addition to the outer envelope and heat exchanger criteria, the PHI has also issued criteria to regulate the energy use and thermal comfort (see Table 3-1).

Table 3-1 Passivhaus criteria (Passepedia, 2015)

Criteria	Passivhaus demand
Heating Demand	$\leq$ 15 kWh/m^2 or 10 W/m^2
Cooling Demand	$\leq$ 15 kWh/m^2 or 10 W/m^2, with additional allowance for dehumidification
Primary Energy Demand	$\leq$ 120 kWh/m^2 for all domestic use, including heating, hot water and appliances
Thermal Comfort	Must be met in all living spaces during winter and summer, with no more that 10% of hours in a given year above 25 °C

Although very specific and stringent criteria are set out by the PHI, the above-mentioned criteria are mostly applicable in cooler climates. Further fine-tuning was required based on the specific climatic region. The latest version of the Passivhaus certification requirements was announced in October 2015, containing a set of new targets for Passivhaus buildings. New classifications were stated for new build, retrofits and the new PHI Low Energy Building Standard. A new addition for a Primary Renewable Energy factor (PRE) and three categories of new build (classic, plus and premium) were announced (iPHA, 2016b; Passepedia, 2015; PHI, 2015e) (see Table 3-2). With the advance and spread of the PH standard to a wider climatic context, inevitable upgrading of the initial criteria was foreseen. The PHI has issued minimum criteria for thermal protection, which would be applicable for building types under the PH standard in different climate zones. The criteria are broken down into two elements – hygiene and comfort. The hygiene criterion is related to the surface temperature of the building components. A minimum temperature factor was developed to ensure that the moisture content within the building components is eliminated within the building. The comfort criterion, on the other hand, covers the maximum thermal transfer coefficients for the different building components within a building. Table 3-3 and Table 3-4 illustrate the comfort criteria permitted by the PH, including the frequency of overheating and excessive high humidity.

Table 3-2 The PH three categories of new build and low energy build (reproduced from recent Passivhaus guidelines (PHI, 2015a))

Criteria	PH New Build				PHI Low Energy Build	
	Criteria			Alternative Criteria	Criteria	Alternative Criteria
Heating						
Heating demand (kWh/m²a)	≤ 15			-	≤ 30	-
Heating load (W/m²)	-			≤ 10	-	-
Cooling						
Cooling + dehumidification demand (kWh/m²a)	≤ 15 + dehumidification contribution			variable limit value	≤ PH req. +15	-
Cooling load (W/m²)	-			≤ 10	-	-
Airtightness						
Pressurisation test result n_{50} (1/h)	≤ 0.6			-	≤ 1.0	-
Renewable Primary Energy (PER)	**Classic**	**Plus**	**Premium**			
PER demand (kWh/m²a)	≤ 60	≤ 45	≤ 30	± 15 kWh/(m²a) deviation from criteria	≤ 75	Exceeding the criteria up to + 15 kWh/(m²a) is permitted
Renewable energy generation (with reference to projected building footprint) (kWh/m²a)	-	≥ 60	≥ 120	With compensation of the above deviation by different amounts of generation	-	With compensation of the above deviation by additional generation

A Passivhaus building, in comparison with a standard building, requires more detailed architectural drawing and better management and control during the construction phase. Additionally, the designer needs to be aware of the best practices that would result in fulfilling the PH criteria. This includes ensuring a well-insulated thermal envelope and a sound selection of ventilating and heating equipment (Brew, 2011). According to Cotterell and Dadeby, *“Achieving Passivhaus is not about lots of ‘advanced’ technology; rather, it is about changing the way we build”* (Cotterell and Dadeby, 2012, pg.31).

Table 3-3 Passivhaus guidelines for thermal comfort *(reproduced from Recent Passivhaus criteria (PHI, 2015a))*

Criteria	Without active cooling	With active cooling
Overheating Percentage of hours in a given year with indoor temperature above 25°C	≤ 10%	Cooling system must be adequately dimensioned to avoid overheating
Excessive high humidity Percentage of hours in a given year with absolute indoor air humidity level above 12 g/kg	≤ 20%	≤ 10 %

Table 3-4 Hygiene and comfort criteria (reproduced from Recent Passivhaus criteria for minimum thermal comfort (PHI, 2015a))

Climate Zone	Hygiene Min. Temperature Factor f_{Rsi}=0.25 (m^2K/W)	Comfort Max. thermal transfer coefficient U-value (W/m^2K)			
Arctic	0.80	0.45	0.50	0.60	0.35
Cold	0.75	0.65	0.70	0.80	0.50
Cool-temperature	0.70	0.85	1.00	1.10	0.65
Warm-temperature	0.60	1.10	1.15	1.25	0.85
Warm	0.55	-	1.30	1.40	-
Hot	-	-	1.30	1.40	-
Very hot	-	-	1.10	1.20	-

3.4 The Passivhaus in Europe

The success of the first pilot project in Darmstadt was the main trigger for the spread of the standard to different parts of Europe. Most of the PH buildings are, at present, found in Germany or Austria. This is perhaps expected, as both countries share similar climates, building technologies and language. In addition, the PH standard had been welcomed very early in Austria and many buildings had been erected following the standard's publication (Müller and Berker, 2013).

Additionally, a number of programmes and projects have been launched in Europe since the first emergence of the standard, such as the CEPHEUS project (1998-2001), the Passive-On project (2005-2007), the Pass-Net project (2007-2010), the PEP project (Badescu, Rotar and Udrea, 2015) and the E-retrofit-kit. The last four projects were financially supported by the Intelligent Energy Europe (IEE) programme.

The IEE programme was originally founded to promote energy efficiency and the development of renewable resources in all domains in Europe, including the built environment. Around 60 projects were supported under the IEE programme's first phase, including the previously mentioned PH projects (Berrutto, Sutherland and Cadima, 2008). The aims of all five PH projects were to determine the feasibility of the PH concept in different parts of Europe and to promote the standard to as many European countries as possible.

The CEPHEUS Project was initiated primarily as a technical feasibility study and a campaign for the German PH standard within the Central European countries. Five countries participated in the project, and over 200 dwelling units were built according to the PH standard in France, Germany, Austria, Switzerland and Sweden. The study's findings were based on measurements recorded in around 100 occupied dwellings located in three of the five participating countries, Germany, Austria and Switzerland. Heating loads, total primary consumption and indoor temperature were the main measured indices. The findings resulted in variable outcomes between the dwellings within the same project or across the different projects in the participating countries. Overall, the outcomes indicated that the PH concepts were achievable outside Germany and that architects and contractors are able to deliver close to PH standards (CEPHEUS, 2001; Schnieders, 2003; Schnieders and Hermelink, 2006).

The Passive-On Project is yet another project that further promotes the PH standard into the warmer parts of Europe. Five countries, France, the United Kingdom, Spain, Portugal and Italy, along with the founding country, Germany, took part in this project. An affordable model meeting the PH criteria was developed in each of the five countries with relevance to the specific designated city climate. The main evaluation aspects included the cooling loads, primary energy consumption and thermal comfort. A set of proposed guidelines for applying the PH standard in warmer climates was the main outcome of the project. The proposed guidelines included an additional cooling load energy limit (that matched the heating load energy limit in cooler climates) to be considered in the warmer climates. A more relaxed infiltration rate (1.0 ach^{-1} @ 50 Pascals) was also suggested for climates that had above 0°C winter design ambient temperatures. Furthermore, in terms of thermal comfort, an operative temperature for hot and warm climates in accordance with the comfort range defined in EN 15251 was suggested, as well as a suggested operative temperature for fully mechanically cooled buildings that remained below 26°C (Passive-On, 2007).

The Pass-Net and PEP projects exemplify other networks and promoter projects in Europe, with different partners involved in each. The Pass-Net project was launched in 2007; the members included Austria, Belgium, Croatia, Czech Republic, Germany, Romania, Slovenia, Slovak Republic, Sweden and the United Kingdom. The programme ran for three years with the focus on spreading the knowledge about the PH standard and providing any required support for both the general public and specialists (Pass-Net, 2010). The PEP network project, on the other hand, ran from 2005 to 2007 and targeted a more specialised audience. SMEs that directly influenced the building stock in the respective countries were the main focus group. The participating countries included Austria, Belgium, Denmark, Finland, Germany, Ireland, Norway, the United Kingdom and the Netherlands. Similar awareness programmes about the standard were promoted through this project, along with guidelines and design strategies specific to each country. In addition, each of the member countries was responsible for establishing a website that provided up-to date information related to the PH development in the country (PEP, 2007).

The E-retrofit-kit was designed to prompt PH retrofitting for housing projects in Europe. The main participating EU members in the programme were Austria, Denmark, Lithuania, Spain and the Netherlands, where the kit was tested and developed. The project provided a web-based tool kit that mainly targeted the PH retrofitting of social housing. Although only four members were the main founders of the programme, the tool kit was made available to as many as 13 different countries in Europe through translation into 11 languages. This included the four founding countries in addition to Belgium, the Czech Republic, France, Germany, Great Britain, Luxembourg, Italy (northern), Portugal and Slovenia. Building typologies and retrofit strategies and best practices were displayed on the website for all 13 respective countries (The E-Retrofit-Kit, 2007).

Other individual studies similarly related to studying the PH feasibility were carried out in different parts of Europe, with the focus on exhibiting the performance of PH buildings and post-occupancy experience in the specific context.

A number of comparative analysis studies were carried out comparing the performance of PH buildings against other energy-efficient buildings. In other cases, the comparison was carried out against a standard building that followed the building codes adopted in the specific country. Outcomes in most cases indicated that the PH approach provided a better performance in terms of thermal comfort and CO_2 emissions and showed a significant reduction in energy use (Badescu and Rotar, 2012; Mahdavi and Doppelbauer, 2010; Rohdin, Molin and Moshfegh, 2014).

An Austrian study assessed the performance of a PH building against a low energy alternative. Two actual apartment blocks were the main subjects of this research; they were part of a project comprising five blocks. One of the apartment blocks contained 27 flats and was built according to the PH standard. The other four blocks were built according to low energy standards in the country and contained 111 apartments in total. Four flats were monitored for five consecutive months, two flats in the PH building and the remaining two in the low energy block. The indoor thermal comfort, energy consumption, costs, embodied energy and CO_2 emissions were monitored and analysed for the four flats. The results indicated that all apartments provided good thermal comfort; this was assessed through the indoor temperature and humidity levels, occupant survey and psychrometric charts. The PH flats revealed a slightly better indoor thermal environment compared to the low energy flats. The study showed a reduced CO_2 concentration in the PH flats, which was attributed to the use of the ventilation system The CO_2 emissions were found to be 24-40%

lower than in the low energy flats. The PH flats even exhibited a 35% reduction of total energy use and 65% reduction in heating energy compared to the low energy flats. However, a higher embodied energy was associated with the PH apartments, in addition to a 5% increase in flat costs compared to the low energy flats (Mahdavi and Doppelbauer, 2010).

The authors' view in favouring the PH option regardless of the increased costs contrasts with research by Audenaert, De Cleyn and Vankerckhove. which was conducted two years earlier. Audenaert et al. (2008) carried out a cost-effective study that compared the energy saving in return to the energy investment of a PH building against standard and low energy buildings in Belgium. Eleven sample buildings were used for the research, three standard buildings, three low energy buildings and five PH-designed buildings. Although less energy-use costs were associated with the PH option, the authors found that the building costs were 16% higher than those for the low energy option. Their recommendation was in favour of the low energy option for its lower investment cost and shorter payback period. The additional PH building costs were found to be linked to the additional insulation layer and ventilation system, but the cost was less for the heating system in comparison to the standard and low energy buildings (Audenaert, De Cleyn and Vankerckhove, 2008).

The difference in views may be related to the fact that Austria and Germany were the first to adopt the PH standard, and share very close architectural styles and technologies (Müller and Berker, 2013). Another factor may be related to the date of the studies, where PH components may have become more affordable after the wider spread of the standard in Europe.

Badescu and Rotar, on the other hand, presented a study that assessed the performance of the PH standard for Romania. A comparative analysis was conducted between the PH standard in Germany and Romania. An existing PH building in Romania was used as a model to perform the comparative analysis; meteorological data were collected from a number of cities in the two countries to perform an energy analysis of the buildings, with the emphasis on heating load and primary energy consumption. The outcomes indicated that the PH standard was achievable for the Romanian context in terms of fulfilling the energy requirements. The study even suggested that, with a relaxed envelope heat transmittance value, the energy requirements could still be met with lower financial burdens (Badescu and Rotar, 2012).

In Northern Europe, specifically in Sweden and Denmark, studies were carried out with the focus on evaluating the thermal performance of PH buildings (Rohdin, Molin and Moshfegh, 2014; Thunshelle and Hauge, 2015). As of 2015, the Norwegian government had announced the implementation of the PH standard in the official Norwegian building code. It should be noted though that the Norwegian PH standard was developed based on the principles of the German PH. It implemented certain criteria of the German PH standard and further developed the remaining criteria based on the Norwegian context (Elswijk and Kaan, 2008). To further assess the performance of PH buildings, a recently constructed school in Norway was the subject of research carried out by Thunshelle and Hauge. The same school was also evaluated by Junghans and Berker against the first German school (Junghans and Berker, 2014; Thunshelle and Hauge, 2015).

The indoor environment of the PH school was found to be better than that of standard schools in Norway. The observations were based on a number of surveys that were carried out for a period of two years by Thunshelle and Hauge. A few issues relating to cold classroom temperatures were resolved by the second year. Additionally, an ongoing awareness in operating the PH and the technical fine-tuning of the ventilation system were the main concerns found in the school. In comparison to the German school, Junghans and Berker reported that both schools provided a better learning environment and good indoor comfort. Although the Norwegian school implemented new technologies, such as automatic blinds and demand-controlled ventilation, these had not affected the degree of satisfaction and energy consumption in comparison to the German school. Additionally, similar to Thunshelle and Hauge findings, the authors pointed out that Norwegian experience found challenges with regard to operating the ventilation system.

In Sweden, the PH standard has also been modified to cope with the Swedish climate. Unlike the Norwegian adaptation to the standard, which included the acceptance of some aspects of the German PH standard with modifications, the Swedish example altered most of the German standard to suit the Swedish context, in addition to introducing specific requirements for different regions of the country (Jacobson, 2013; Wahlström et al., 2008). A study conducted in Sweden assessed the thermal performance and energy use of PH buildings built according to the Swedish PH standards. Building simulation, CFD analysis and field surveys were used to evaluate the performance of PH buildings against standard buildings within a residential project. The project, comprising 39 terraced houses, was composed of nine houses constructed according to the PH standard, while the rest were constructed according to the conventional practices in the country. The PH buildings, compared to the conventional model, were better insulated and airtight and, in addition, used passive heating. A heating coil was added in the heat recovery unit of the PH models to provide additional heating if needed, while the conventional houses were equipped with regular radiators. Both dwelling types used a ventilation heat-recovery system. The findings indicated that both building types had, in general, performed well. Some issues were indicated, though, in the PH-type buildings. These included variable indoor temperatures, overheating during summer, cold floors and a higher degree of poor air quality (Rohdin, Molin and Moshfegh, 2014).

Further studies have focused on risks that may be associated with implementing the PH standard. Many studies found that overheating might be an issue for PH buildings, although the PHI has declared that with careful design and consideration the issue could be resolved by simply operating the ventilation system effectively to bypass heat recovery or even just by opening the windows. In addition, with the aid of the PHPP, overheating risks can be dealt with during the design process by carefully designing the glazed surfaces and associated shadings (Junghans and Berker, 2014).

Brunsgaard, Knudstrup and Heiselberg (2012) analysed a number of studies that were set out in different parts of Europe to assess the thermal comfort of Passivhaus buildings. Issues related to overheating were found to be raised in a number of the examined studies. This was cited mainly for projects carried out in Sweden and Denmark. The authors pointed out that, similar to the above-mentioned Swedish study, a number of houses in Sweden built according to the PH criteria had suffered from variable temperature, cold floors and rooms, and overheating. In general, though, the indoor environment during the winter was found to be satisfactory. The authors also included outcomes of the specific Danish experience. The Comfort Houses project was one of the first PH projects carried out in Denmark. Nine different PH single-family houses were built and certified according to the German PH standard. Semi-structured interviews were used to evaluate the performance of the PH buildings, at the beginning and after 6-10 months of occupancy. The authors concluded that most occupants had experienced overheating and needed educating on how to effectively operate the ventilation system and utilise natural ventilation (Brunsgaard, Knudstrup and Heiselberg, 2012). The study related to both the social and technical impacts of living in a PH building and provided a glimpse into how occupants interact with PH buildings. A possible long-term assessment would have provided an even better understanding of how people use PH buildings differently.

A London post-occupancy study evaluated the first Passivhaus building in the city, known as the Camden Passivhaus. The outcomes agreed with the Danish study to some degree, with one occupant finding that the heating controllers were confusing to use. Additionally, a number of building simulation tools predicted that the house would be overheated in summer, although the occupants claimed that they enjoyed the warmth of the summer. Furthermore, a slight increase in primary energy demand was observed in the house which, according to the authors, could be resolved by amending the hot water system and solar heating. Despite the marginally increased primary energy load, the Camden house is considered one of the lowest-operating energy-efficient houses in the UK (Ridley et al., 2013).

Finally, an example of the PH standard not being achieved is represented in a study carried out in Estonia. Two non-residential buildings were intended to achieve PH criteria – a renovated nursery and a newly built community centre. However, the two buildings failed to meet the PH criteria for primary energy and heating loads. In addition, the community centre’s envelope was found to be not as airtight as specified by the PH standard, and with a number of thermal bridges. In general, the authors indicated that the reasons behind these shortcomings were mainly related to errors in calculation during the design phase and problems in the operation and management of the ventilation and HVAC systems (Raidea, Kalameesa and Mauringb, 2015).

Through the different projects and studies, the Passivhaus standard has been shown to be mainly successful in Europe, achieving a reduction in energy consumption of up to almost 80%. The design principles of the PH standard enabled buildings to be heated with the minimum energy, while ensuring comfortable winter conditions. A risk was found to be associated with the issue of overheating during summer; this was evident in a number of post-occupancy surveys carried out mainly outside Germany, where architectural solutions for PH building were variable. Nevertheless, with careful engineering and through understanding of the PH principles, the problems of overheating could be readily solved.

3.5 The Passivhaus in different climate zones

"While Passive House buildings are held up to stringent quality criteria, the concept itself is very flexible and can be adapted to a variety of building uses and almost any building style. As the Passive House concept is based on physical principles, each building can and should be adapted to its particular climate" (iPHAb, 2015).

The wide success of the PH standard encouraged many architects and engineers outside Germany to test the validity of the standard in different settings. Based on the Passivhaus database, the PHI has certified a number of projects in different parts of the world, mostly in North America and Asia, and a few in Australia and South America (Passive House Database, 2014).

Furthermore, many voluntary PH buildings have been erected all over the globe, although not all may have been identified as certified buildings in the PH database, or have even gained the PH certification. Green building magazines, blogs and different media sources have reported the continuing emergence of PH buildings in different and challenging locations. Examples include a PH research centre in Antarctica, a family retreat in South Africa, an embassy in Indonesia and a villa in Qatar (see Figure 3-3) (Ciobanu, 2015; Jesse, 2011; Killough, 2014; Meinhold, 2014). However, in spite of the existence of certified and non-certified Passivhaus projects outside Europe, only a few published new-build performance and post-occupancy-related studies have been produced.

Long-term post-occupancy studies for two Passivhaus buildings in the USA, in Illinois and Louisiana, indicated that the buildings had performed well and had achieved very close to PH criteria. Concerns related to total primary energy consumption and latent loads were found to be the main factors that failed to fulfil the Passivhaus criteria (Helton, 2012; Stecher and Allison, 2012).

The Illinois Passivhaus building, known as Smith House, was completed in 2009, and has undergone a monitoring period of two years. Around 100 sensors were used for monitoring the house. Two aspects were fully investigated – the electrical consumption and the cooling thermal comfort performance of the ductless mini-split heat pump. The outcomes indicated that a slightly greater heating load compared to the PH criteria was evident; in addition, latent cooling loads were greater than anticipated. Finally, the cooling and heating systems were found to provide reasonable temperatures close to the assigned set points.

The Louisiana Passivhaus building, known as Le-Bois House, was monitored for 18 month after its completion in 2010. Twelve Onset loggers were used to measure the temperature and humidity of the interior, exterior and basement of the building. A similar assessment was carried out in comparison to the Smith House: electrical consumption and thermal comfort were compared against the values predicted through simulation. The heating and cooling loads were found to be lower than predicted while, in comparison, a higher total primary energy demand was found. The thermal comfort was found to be just about maintained during the summer (Helton, 2012).

(a) Research centre in Antarctica

(b) Family retreat in South Africa

(c) Embassy in Indonesia

(d) Villa in Qatar

Figure 3-3 Passivhaus projects in extreme climates (Ciobanu, 2015; Jesse, 2011; Killough, 2014; Meinhold, 2014)

Broniek with the support of the U.S. Department of Energy's Building America Program investigated the feasibility of the Passivhaus standard for different climatic zones in the US. The study incorporated parametric modelling using a building simulation software in addition to the Passivhaus Planning Package (PHPP). A model was created and situated in two cities within each of the three zones; heating and cooling loads were analysed to reach the PH criteria. The outcomes suggested that it may be more feasible to build in the mixed humid zone, whereas it would be more challenging in the cold and hot humid zones (Broniek, 2008).

In New Zealand, a comparative study was conducted to assess the performance of the PH retrofit scheme against the standard retrofit practices in the country for historical buildings. A typical historical building was selected to address the impacts of applying PH retrofit on the indoor environment, air quality and airtightness. Prior to simulation, actual on-site measurements were recorded in the selected house and two other base houses. A number of variations were conducted using a building simulation tool and the PHPP tool reaching the full German PH retrofit recommendations. The tested scenarios indicated that it may not be feasible to fully reach the PH retrofit standard. The change of construction market, socio-cultural backgrounds and economic burdens may create challenges for the full adaptation of the retrofit standard, although the PH standard has been applied to new builds in New Zealand since 2011. The authors concluded that further enhancements of the building envelope, in terms of detailing thermal bridges and airtightness, would be required for the retrofits in the region for future applications (Leardini, Manfredini and Callau, 2015).

A similar approach was undertaken in Canada, where the building airtightness and outer envelope were optimised for the Canadian context. A parametric study was performed to enhance a designed PH building in North America. Two parameters were assessed in the study, the glazed wall U factor and the building airtightness level. The performed parametric study indicated that, for cold climates, isolation and airtightness were the two main factors that contributed to achieving less energy use in the built environment (Kim and Han, 2014). The two latter-mentioned studies have pointed out two main aspects to achieve energy efficiency and to reach PH standards. The first is the improvement of the building fabric, through the introduction of isolation and airtightness, and the second is the implementation of an effective heating or ventilating system.

Other comparative studies were carried out in South America, specifically in Brazil and Chile, to assess the performance of the PH in the particular context. Tubelo, Rodrigues, and Gillott (2014) reported a comparative analysis between the PH standard and the voluntary Brazilian labelling code for domestic buildings. Although direct comparison could not be executed due to the variable nature of the codes, the aims, criteria and assessment method were investigated. The PH standard was found to be focused on thermal comfort with minimum energy use, as opposed to the energy-saving aspect found in the Brazilian code. Further study was recommended in regard to the PH's thermal envelope criteria, as the Brazilian code was oriented towards a more relaxed envelope that permitted natural ventilation. Therefore, less stringent envelope criteria, such as higher U-values and infiltration rates, could be revisited to better suit the Brazilian context (Tubelo, Rodrigues and Gillott, 2014).

On the other hand, Carrasco Eade and Kokogiannakis (2012) carried out a feasibility study of the PH in the Chilean context. Comparative analysis was conducted using dynamic simulation to evaluate the performance of the PH approach against the Chilean building envelope code for a typical residential building. Further solar passive techniques were incorporated into the typical house design and a parametric study was performed to achieve the optimum case for the Chilean house. The outcomes indicated that incorporating less stringent PH envelope criteria along with a solar passive design would improve energy saving and would be a feasible option in the Chilean context (Carrasco Eade and Kokogiannakis, 2012).

Finally, parametric studies were carried out by the German Passivhaus Institute for different climates. Two reports were issued, in 2012 and 2013 respectively, '*The Passive Houses for Different Climate Zones*' and '*The Passive Houses in Tropical Climates*'. Both studies provided technical recommendations based on a number of dynamic and steady-state simulations for the specific climatic zones (Passepedia, 2015). Schnieders, Feist and Rongen (2015) published, in collaboration with the PHI, a paper derived from the 2012 report. The paper showcased that the PH concept could be realised anywhere in the world, no matter what the climate or building type. Moreover, further elasticity in the stringent German PH criteria was evident through the variable cooling and heating loads presented in the paper, in addition to a higher U-values for building components.

The trend to adopt energy-efficient practices is spreading rapidly, and the Passivhaus standard provides a strong basis for achieving ultra-low energy buildings. In 2013, a new Passivhaus building was announced in the Gulf Cooperation Council (GCC) region. Qatar, a member of the GCC countries, had completed the first experimental PH project in the region, which is considered to be a precedent for the PH standard in the region (Hartman, 2013).

3.6 Passivhaus Buildings in Hot Climates

The success of the Passivhaus standard, and its straightforward approach are perhaps the main drivers towards the wide spread of the Passivhaus standard to different parts of the world. Many projects, either voluntary or certified by the PHI, have been constructed in regions with extreme weather conditions compared to where the standard had originated in Germany. Three cases will be demonstrated to discuss the implications of the Passivhaus standard in hot climates, two actual buildings and one virtual model. The first Passivhaus building is the Austrian embassy in Jakarta, Indonesia, the second is the Le-Bois house in Louisiana, USA, and finally a virtual model in Dubai, UAE, illustrated in the PHI report, "*The Passive house for different climate zones*".

3.6.1 The Austrian embassy in Jakarta, Indonesia

The Passivhaus embassy was completed in 2011, and is considered to be not only the first green embassy in the world but also one of the Passivhaus projects in hot and humid climates (see Figure 3-4 and Figure 3-5). The masonry-constructed structure covers around 1000 m^2 of usable area, and is mainly used as an office building, housing 20 working spaces, the visa office and a convention hall (Oettl, 2014).

The embassy resembles a sustainable design that is climate sensitive. Considerable attention was given to the climatic conditions of the region, resulting in a number of design strategies that helped to form the Passivhaus Austrian embassy. Significant detailing was carried out to achieve the optimum outer fabric configuration. First, the building axis was oriented towards the north - south, ensuring that glazed surfaces were located on the main axis façades. Second, careful attention was given to the ratio of the opaque to clear surfaces, and added solar protection was considered for these surfaces. The glazed surfaces were deeply recessed and well insulated; timber screening was used to shade the walls and roof of the building. The building shell was highly insulated and airtight, achieving an airtightness level of 0.45 air changes per hour at 50 Pascals with a blower door test. The overall annual energy demand was estimated at 117.1 kWh per m^2 of treated floor area using the Passive House Planning Package (Passive House Database, 2016). Approximately

22% of the annual energy is generated via the 96m^2 photovoltaic generator placed on the roof (Oettl, 2014).

Cooling demand in the building was met by using a thermo-active building system, where the thermal structure of the building was used to cool the building through the use of a concrete core temperature control system (Oettl, 2014). This eliminated the need for conventional air-conditioning and ensured a comfortable indoor environment. In addition, a ventilation system with a cooling recovery and dehumidification was used to provide fresh air to all the office spaces in the building. Finally, solar water heating was used for the hot water demand (Passive House Database, 2016).

Figure 3-4 Main façade of the Austrian embassy in Jakarta (Oettl, 2014)

Based on an initial correspondence by the author with officials in the embassy, it was conformed that monitoring of building’s performance was being undertaken to measure its actual performance. Unfortunately, the performance data were not made available for this research to further assess the performance of other Passivhaus buildings in hot climates.

Figure 3-5 Jakarta embassy ground and first floor layout (Oettl, 2014)

3.6.2 The Le-Bois house in Louisiana, USA

The 120m^2 Passivhaus building is located in Lafayette in Louisiana, USA. The double-storey building was used as three bedroom student accommodation (see Figure 3-6). The idea of the project was initiated by an architect, Professor Corey Saft, from the University of Louisiana, with the main purpose of experimenting with the possibility of adapting the Passivhaus concept in the hot humid region of southern USA (Goodman, 2012) The house, named later as "Le Bois", was constructed in 2010 and underwent 18 months of extensive monitoring.

Figure 3-6 Le-Bois house in Louisiana (Saft and Helton, 2012)

Advanced framing was used in the construction of the house, which allowed a reduction in material, labour and cost, while also eliminating thermal bridges. Insulation layers of 25mm and 50mm thick were used for the wall and roof respectively. Shading to the building was provided through a rain screen which simultaneously acted as a moisture management control system. A 3.2 kW solar cell was mounted on the roof of the house, covering on average 40% of the primary energy consumption. PHPP was used to model the energy performance of the house; the cooling load was estimated at 15kWh/m^{2}a, the heating load as 8kWh/m^{2}a, and the primary energy as 116kWh/m^{2}a. However, the actual measurements taken over the course of 18 months concluded variable results. The house actually used less energy for both cooling and heating. The utilised cooling energy was measured at 10.6kWh/m^{2}a, and the heating load at 0.6kWh/m^{2}a. The specific primary energy use was measured at almost 50% higher than expected at 184kWh/m^{2}a. (Saft and Helton, 2012).

The house benefited from a mini-split heating and cooling system, and an energy recovery ventilation system (ERV). The two systems served two main zones, the private zone comprising the three bedrooms, and the public zone, which included the living/kitchen area (see Figure 3-7). The mini-split air-conditioner was placed in the double height space within the living area. It primarily cooled the public zone, and partially cooled the private zones when the doors were kept open. The ERV, on the other hand, served fresh air to all the zones (Helton, 2012).

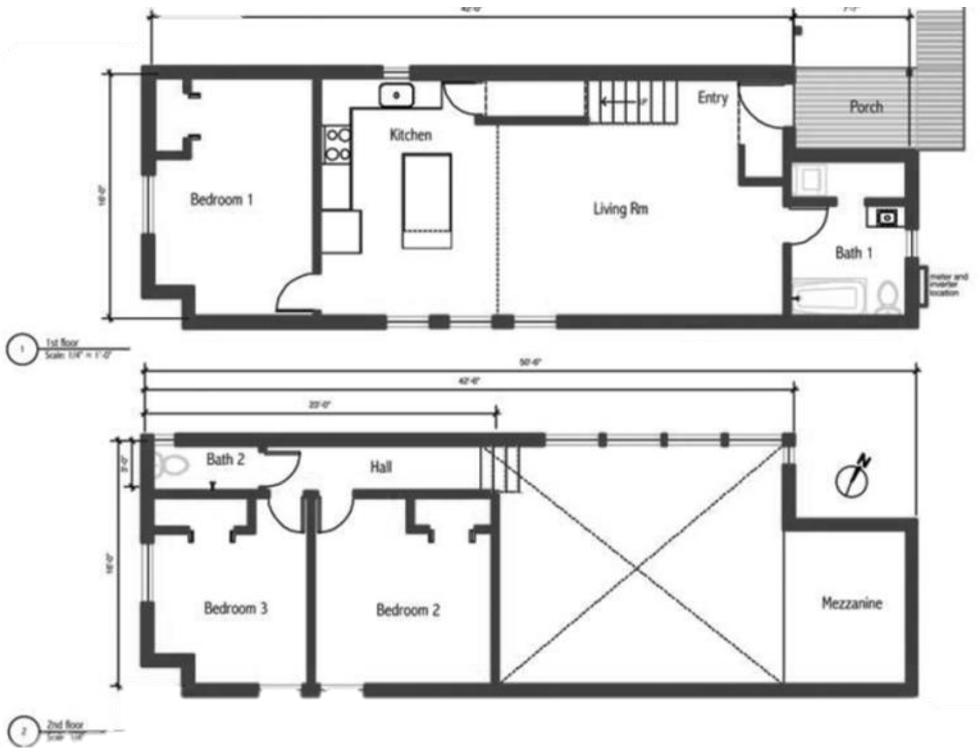


Figure 3-7 Le-Bois house ground and first floor layout (Saft and Helton, 2012)

3.6.3 Passivhaus model in Dubai, UAE

'*The Passive House for Different Climates*' report issued by the Passivhaus Institute included examples of Passivhaus buildings in five locations with extreme climates, one of which was Dubai, UAE (Schnieders et al. 2012; Schnieders, Feist and Rongen, 2015). The proposed models were based on parametric studies that were undertaken on a base model for all five locations to conclude the design strategies required for each location.

The Dubai example building incorporated a two storey detached family house, with 354.4m^2 of total treated floor area. The building was designed as a modular unit that could be detached, semi-detached or attached based on the arrangement of the modular units. The model was a two storey house, with the basement floor fully buried underground, and a ground floor. Two courtyards were incorporated into the design, one acting as an entry courtyard partially open to the street, while the other resembles the heart of the design. Openings to the outdoor were eliminated, and were alternatively directed towards the main courtyard to reduce direct solar transmittance through the glazed surfaces (see Figure 3-8). The basement level included the bedroom spaces, while the ground floor incorporated the living and guest spaces. Shading and evaporative cooling had been integrated into the design of the main courtyard to provide added protection against the high insolation levels. Other special features, such as solar water heating and grey water systems, have been included in the design of the Dubai model to increase its energy effectiveness.

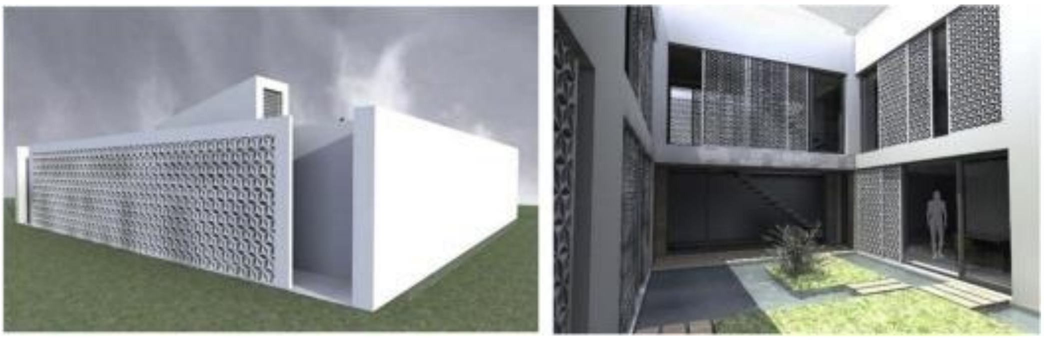


Figure 3-8 Dubai model Passivhaus building (Schnieders, Feist and Rongen, 2015)

To achieve Passivhaus standard levels, the thermal envelope was treated using various insulation material types and thicknesses to reach high levels of airtightness and reduce heat gain to the minimum. Thermal insulation was used on the walls, roof and floor for thicknesses ranging from 150mm to 300mm. The glazed surfaces were triple glazing. Additionally, cool colours were used for the wall and roof surfaces. The cooling loads in the design had been reduced to 10W/m^2 by adopting the latter mentioned strategies; the specific cooling demand, however, was estimated at 32kWh/m^{2}a due to the prolonged cooling season, which lasts for six months during the year. The specific primary energy demand was estimated at 87kWh/m^{2}a, presumably by implementing high efficiency lighting, systems and household appliances. Mechanical cooling and ventilation with heat and humidity recovery was used in the model due to the high temperatures and humidity levels that were expected during the summer months.

3.7 Summary

The Passivhaus standard has become one of the most widely spread energy-efficient measures around the world. Although many technologies have been developed over recent years, the PH standard seems to be one of the most intriguing for researchers to explore

(Dequaire, 2012). The reasons behind this rely on the amount of research and publicity that has been carried out by the Passive House Institute in Germany. In Europe, similar energy efficiency approaches have been developed that closely match or even exceed the PH standard but very few have managed to gain the widespread impact of the PH standard. A clear definition, a vast amount of accessible information and a continued upgrading of the standard by the founding organisation have added to the spread of the standard (Müller and Berker, 2013). It has been noted that a number of programmes within Europe have been dedicated to the PH standard. Projects such Pass-Net and PEP projects aimed to spread awareness of the technologies associated with the standard in the specific context of each EU member (Badescu, Rotar and Udrea, 2015). In addition, a number of studies have been carried out by the PHI, such as the CEPHEUS and the Passive-On project in Europe. Furthermore *the 'Passive House in Different Climate Zones'* and '*The Passive Houses in Tropical Climates'* reports issued by the PHI offer guidance and design strategies for the application of the standard to different climate zones (Passepedia, 2015).

It was also noted that, in comparison to other energy-efficient typologies, the PH standard offers a better-structured set of criteria to follow that have been tested and proved to succeed. A number of studies have been carried out mainly around Europe to assess the performance of the PH in variable contexts (Müller and Berker, 2013). The outcomes in the majority of them indicated that results very close to those promised had been achieved, especially with regard to energy use and reduction of heating demands. Challenges and risks that were associated with the PH buildings were mainly associated with overheating risks during the warmer seasons and in warmer climates in Europe. Additionally, concerns related to the occupants' ability to operate the heating and ventilating systems correctly were raised in a number of studies. It has been argued that an induction on how to operate a PH building will be necessary prior to using a Passivhaus building, making this a possible constraint to effectively achieving a PH standard, in addition to the changes required in construction skills and detailing (Brunsgaard, Knudstrup and Heiselberg, 2012; Junghans and Berker, 2014; Leardini, Manfredini and Callau, 2015; Raidea, Kalameesa and Mauringb, 2015; Ridley et al., 2013).

Recently, the PHI has issued revised guidelines to allow the adaptation of the standard in different climate zones. The Passive House Planning Package, which is the main energy tool used by the PHI, has been updated to allow for implementation in different climatic contexts (PHI, 2015e). This chapter has highlighted the PH standard by exhibiting a number of studies that have been carried out in Europe and around the world.

The success of the PH standard and the precise set of requirements were the two main motivators that contributed to the selection of this energy-efficient standard for this study. The next part will illustrate the assessment tools and methods used to conduct the research. This is followed by a detailed description of the Passivhaus project in Qatar, including its emergence, technical and architectural detailing.

Part 2

Descriptive Review

Chapter Four
Assessment Tools and Methods

4 Assessment Tools and Methods

4.1 Overview

A research focus of recent years has been directed towards evaluating the performance of new building typologies and technologies. With the emergence of energy-efficient buildings, and the production of new advances and technologies in the built environment, testing and evaluation provide assurance for clients and policy makers concerning the adoption of these new trends. Additionally, due to the identification of a performance gap between the predicted and the actual building performance, assessment tools and monitoring processes have been sought as a means of reducing uncertainty with respect to the performance gap. A number of parameters are normally assessed in buildings, including energy use, envelope performance and the indoor comfort levels. These parameters can provide a better understanding of how a building actually works, or even how a new standard or technology can be improved for future use. Ratification of any faults is made possible and a better performance can be achieved in the new building typologies (Guerra-Santin and Tweed, 2015a). Numerous tools can be applied during the assessment process, although many argue that it may be time-consuming, expensive or may need expertise to be executed in the right manner. Despite these arguments, researchers from different parts of the world have produced significant findings based on the use of assessment and monitoring tools. Affordable monitoring equipment and a dedicated research budget, time and effort may be the key elements for the production of a vast number of performance related studies. The framework for the performance assessment of any project starts with the design process, which sets the initial benchmark for the building. This is usually followed by a post-construction evaluation which ensures that the building envelope and its systems are built and functioning according to the design. Finally, a post-occupancy assessment includes the human factor in the matrix, introducing the most complex and unpredictable element of all (O'Leary et al., 2015; Guerra-Santin and Tweed, 2015a; Sodagar and Starkey, 2016). In this research, the original aim was that the three stages (design, performance assessment and post-occupancy assessment) would be implemented for the Qatar Passivhaus. However, due to unforeseeable difficulties with sponsorship and ownership changes of the Passivhaus, it was not possible to perform all phases in the detail originally envisaged. However, it has been possible to use the Passivhaus as a framework for a detailed modelling and monitoring study.

4.2 Assessment Framework

This research was based on the assessment of a pilot Passivhaus project in Qatar that was initiated by the Qatar Green Building Council (QGBC) with the primary project team headed by Dr Alex Amato. The Passivhaus, and a near-identical adjacent 'standard' house, were designed by a team of experts, and were intended to undergo a period of extensive monitoring and post-occupancy studies. The first house, called the Passivhaus villa (PHV), was built according to the German Passivhaus standard, while the other was built according to the normal practices in Qatar, and was named the standard villa (STV).

A building management system (BMS) and a weather station were to be installed in the house providing information related to the performance of the buildings. The monitored data were intended to include energy use, water use, photovoltaic (PV) energy production and the indoor environment. In addition, two families, most likely non-Qataris, were to be selected to inhabit the houses to take part in the post-occupancy study section of the experiment. Due to financial and administrative difficulties, the monitoring and occupancy did not take place as scheduled. Despite that, the management team in Qatar did not spare any effort to engage many researchers in the project, and rigorously took every opportunity to resolve the project's administrative issues.

To overcome the lack of monitored data from the villas, the author visited the villas several times during this study. She positioned HOBO temperature and relative humidity data loggers in the villas for periods of several weeks. Additionally, a colleague from the original Qatar Green Building Council team went to the villas to record sub-meter readings that were used to evaluate the energy use of the cooling system and household appliances.

This approach provided the means of evaluating some aspects of the villas' actual performance. Although this method seems to be very modest in comparison with the initial monitoring targets, the data loggers were able to capture some of the indoor environmental conditions in both houses. Analysing these measured data has provided a degree of confidence towards an initial assessment of the project as well as providing validation data for comparison with thermal modelling of the villas.

It should be noted that the houses, although not occupied at the moment, are both fully operating. The cooling system, lights and other casual household usages are maintained in the villas. Occasional site visits are arranged by the QGBC team for students and researchers. Furthermore, a number of studies, in addition to this research, are being carried out to assess the performance of the project, such as the performance of the roof-mounted photovoltaic array on the Passivhaus villa and a comparison of the two building standards used for constructing the two houses.

This research was based on the evaluation of the Passivhaus villa in Qatar by utilising a number of tools to measure the performance of the Passivhaus villa against the standard villa and in comparison to the German Passivhaus standards. Assessing the project is important because it will provide a degree of confidence concerning the actual performance and feasibility of the Passivhaus standard in a hot and arid climatic zone.

First, a building simulation tool was used to predict and compare the energy use and thermal comfort levels in the two houses. Second, on-site measurements were recorded to obtain the actual energy use and indoor environment in the two houses. The actual measurements were compared to the predicted energy use and thermal comfort levels. Finally, a future evaluation of the project was performed by placing the two houses in future weather scenarios for the same location using the same building simulation tool to further assess the feasibility of the standard under climate change scenarios. Figure 4-1 illustrates the framework used to assess the buildings' performance.

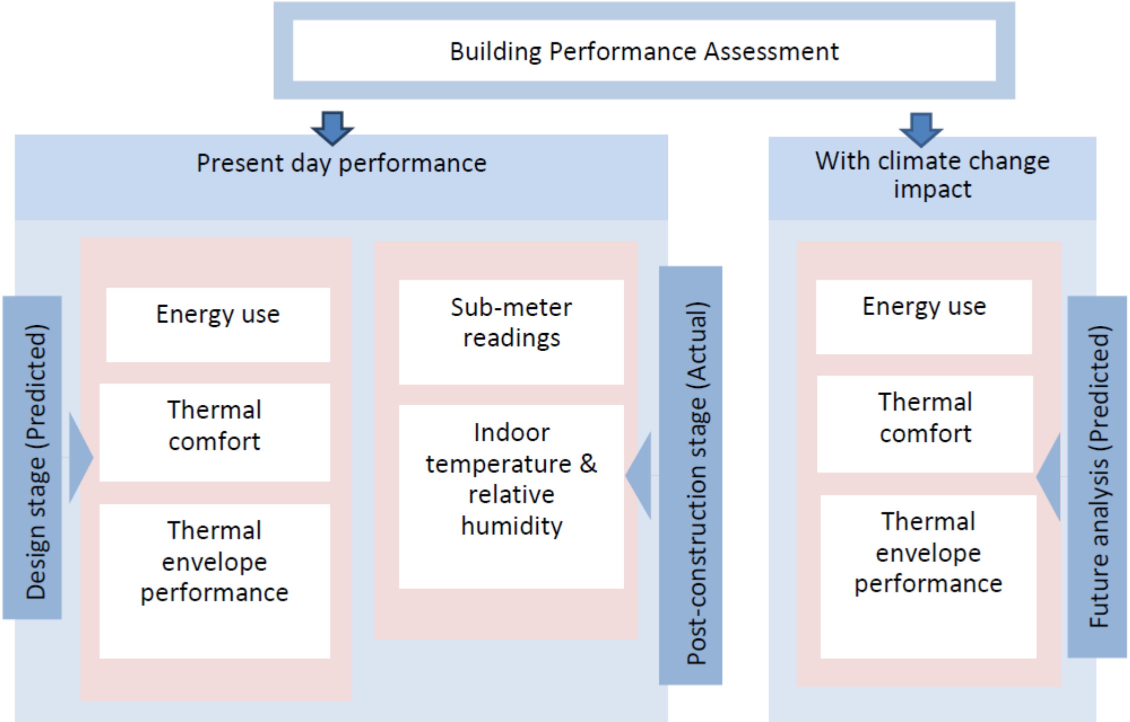


Figure 4-1 Building assessment framework

Furthermore, a parametric study was carried out to bridge the performance gap between the PHV and the STV. The robust feature of the Passivhaus villa, its outer shell, was used as the main bridging element. A number of scenarios were performed using a building performance simulation tool to evaluate the effects of fortifying the outer shell of the STV in comparison to the PHV. This was mainly carried out as an attempt to further safeguard the standard villa and transform its performance, possibly bringing it closer to Passivhaus standards by fine-tuning the most crucial element of the building, i.e. its outer envelope.

The following sections will address the measurement tools used in the study, by discussing the reasons behind selecting the specific tools, and how they were integrated into the assessment process.

4.3 Building Simulation Tool

“Simulation represents a possible solution to the complexity dilemma by enabling comprehensive and integrated appraisal of design options under realistic operating conditions” (Clarke, 2001, pg. ix).

As the world is heading towards an energy conscious and efficient era, Building Performance Simulation (BPS) tools have been extensively used in many building performance-related studies. In fact, Building Performance Simulation (BPS) tools have become an essential and integral tool during the design of buildings in many developed countries (Nadarajan and Kirubakaran, 2016). According to Crawley et al. (2008), BPS tools have been in use for over 50 years. BPS tools are used for decision making during preliminary design or final design stages. They aid designers, engineers and decision makers to comprehend the expected performance and expenses related to any project. Thermal comfort, energy performance, CO_2 emissions, energy costs, energy assessments and building life cycle are some examples of measurements obtained from BPS tools (Maile, Fischer and Bazjanac, 2007). BPS tools also enable the evaluation of different design alternatives and predict their effects in a single project.

According to Attia et al. (2012b), around 400 BPS tools are available, making the selection process a daunting task for architects and engineers, although the selection may be only the first obstacle that architects face; other challenges are related to actually being able to effectively use the tool itself. BPS tools are complex systems that require training and precision in the input data in order to get close to real outcomes.

In this research the Integrated Environmental Solutions – Virtual Environment (IES-VE) software was selected for producing the virtual model of the two houses. During the initial phase of this research a decision had to be made in regard to the selection of the BPS tool, and the choice came down to two BPS tools. The first was DesignBuilder, which was the most commonly used BPS tool amongst researchers in the University of Liverpool. The other choice was IES-VE, the software used by the team in Qatar to perform their initial studies. In order to make an informed choice, an introductory self-training exercise was carried out by the author for both tools by performing a simplified assessment.

Additionally, a number of articles were reviewed that compared the tools, either against each other or against other BPS tools (Attia et al., 2012 a; Attia and De Herde, 2011; Attia et al., 2012 b; Crawley et al., 2008; Maile, Fischer and Bazjanac, 2007; Weytjens et al., 2011). Based on the preliminary comparison process, IES-VE was the preferred BPS tool for a number of reasons. The software has a friendly graphical interface and seemed to be a comprehensive environmental suite that would provide a further continued learning curve. Online training, forums and face-to-face training were easily attainable, making the learning process less overwhelming. Additionally, having the existing QGBC model in IES-VE made cross-referencing for errors an easier task, making this software the tool of choice.

IES-VE is an innovative 3D sustainable analysis software pack used to measure and manage sustainable, efficient and affordable built environments. Dynamic simulation through the IES module Apache-sim is based on first principles of mathematical modelling of heat transfer processes in and around the building. IES has been validated and tested against a number of standards, such as ASHRAE 140, USGBC and BEST TEST (IES, 2016). Amongst the inputs required in IES are: (1) a compatible weather file based on the location of the project, (2) the geometrical configuration of the building and its exact orientation, (3) the building's construction data and thermophysical properties, (4) HVAC system input and (5) occupancy and household operational schedules (Harish and Kumar, 2016). The working drawings and the original IES-VE file provided by the team in Qatar through AECOM-UK, a partner involved in the design process, became the main two documents that were used to construct the two villa models in IES-VE.

4.3.1 Weather data sets

BPS tools require hourly weather data sets to complete the building performance analysis for the exact location of any project. Weather files specifically represent the climate of the selected location and normally include variables such as dry bulb and wet bulb air temperatures, relative humidity, solar radiation, wind speed, wind direction and cloud cover etc. for each hour of the year. The most commonly used weather file formats are the Typical Meteorological Year (TMY2) and the EnergyPlus Weather (EPW) file format (Energy Plus, 2016). IES-VE can read an EPW file and FWT file, which is a proprietary file type of IES

(IES, 2016). Weather files can be readily downloaded online through a number of websites, such as the Energy Plus website, for a vast number of locations, or can even be embedded in the BPS tool itself. For locations that are not readily available, weather files can be generated through a number of commercially available weather generator tools, such as Meteonorm. Meteonorm is a comprehensive meteorological reference weather generator tool that provides a number of weather data formats for almost any location around the globe. Meteonorm uses data available from weather stations for the selected locations by stochastically generating typical years from interpolated long-term monthly means (Meteonorm, 2016).

The hourly weather files available through websites or in BPS tools are historical weather files sets which present weather data based on hourly climate observations for a number of years in the past (Crawley, 1998; Crawley, Hand and Lawrie, 1999). Architects and engineers today are not only interested in the current performance of buildings, but may also want to understand the performance of buildings under future climate change impacts.

A similar approach has been adopted towards the assessment of the project in Qatar in this study. The houses' performances were considered for two time frames, the present time and in the future. Therefore, Qatar weather data were required for the two time frame sets. Qatar's weather files, however, were not readily available on either the Energy Plus website or the built-in IES-VE weather files. Meteonorm was therefore used to acquire a present-day weather file and future weather files in EPW format.

The Climate Change World Weather Generator (CCWorldWeatherGen) is a software package developed by the Sustainable Energy Research Group at Southampton University that is able to generate future weather files. Two sets of future weather files were consequently created for this research according to IPCC scenario A2, for the years 2020, 2050 and 2080. This was based on the CCWorldWeatherGen available climate change scenarios. The reason behind considering two sets was mainly to compare the predicted weather data sets using the same present-day weather file. The nature of the scenarios is surrounded with a degree of uncertainty as they are based on assumptions on how the future may unfold, depending upon observations and projections of behaviours or concentrations of certain gases. In addition, other uncertainties are associated with the use of BPS tools and weather file generation. Therefore, to further assess the future weather files for Qatar, the two approaches (Meteonorm and CCWorldWeatherGen) generated future data sets for comparison purposes.

The software Climate Consultant was used to visually represent the historical climate of Qatar (see Figure 4-2) and to compare between the future weather EPW files generated using Meteonorm and CCWorldWeatherGen (see Figure 4-3 and Figure 4-4). Climate Consultant 6.0 is a graphical-based visual tool developed by the University of California, Los Angeles (UCLA) Energy Design Tools Group; it is readily available for free download through the UCLA website. Climate Consultant provides a visual representation of EPW files; in addition, the tool provides strategies for the examination of indoor comfort (UCLA, 2016).

The comparisons between the future weather data sets for Qatar were extracted from Climate Consultant. Climate Consultant allows the exporting of weather variables from the original EPW file on an hourly, monthly and daily basis, to a Comma Separated Values (CSV) format.

The future weather file sets used were morphed based on the same historical weather file, and projected to the A2 scenario (medium to high impact), which could be estimated to be between the high and medium Representative Concentration Pathways (RCPs) recent scenarios. The comparison of the two file sets indicated that the CCWorldWeatherGen provided a slightly higher value of dry bulb temperature and consecutively a lower relative humidity level, as shown in Figures 4-3 and 4-4.

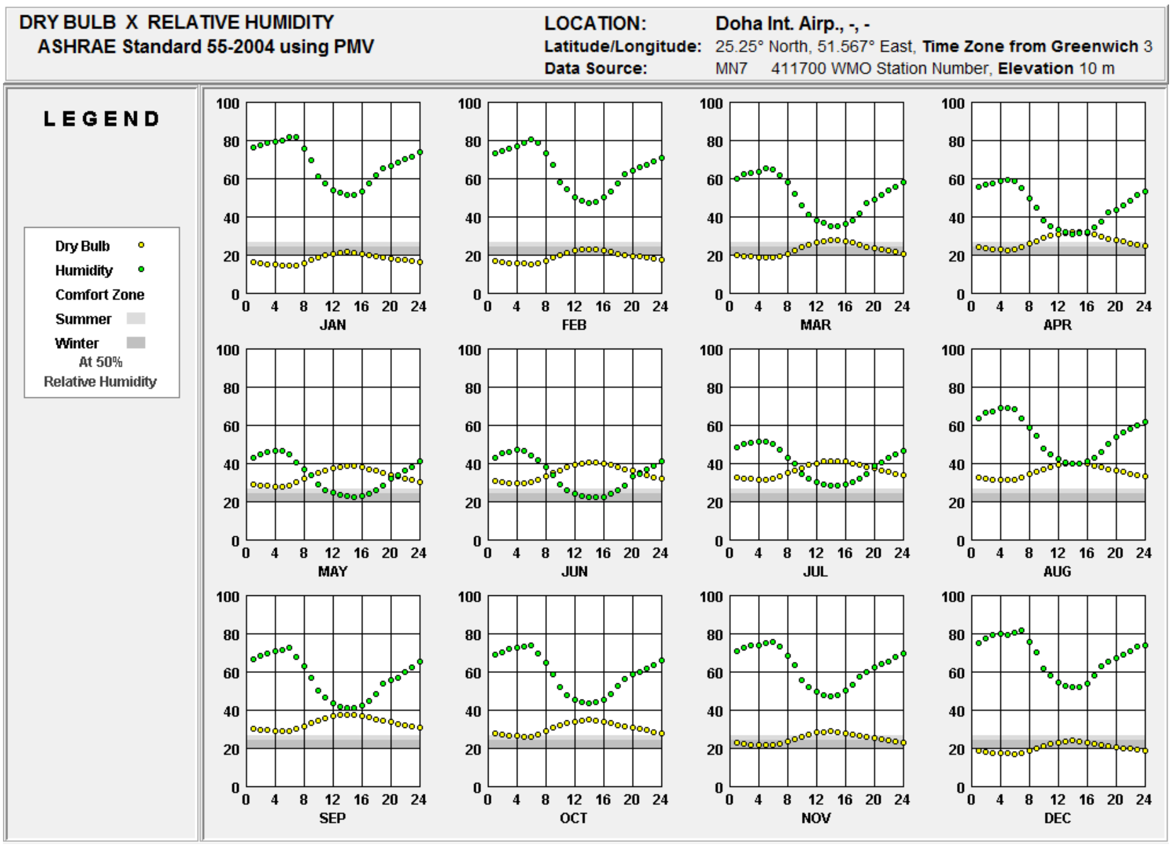


Figure 4-2 Qatar's present climate (Climate Consultant 6.0, 2016)

This could be attributed to the different calculation methods and morphing processes embedded in the two tools. On average, the CCWorldWeatherGen tool future weather files predicted dry bulb air temperatures higher by around 1.5°C-2.8°C compared to Meteonorm, with an average difference of around 6-9% in the same time series. The difference reached its peak of around 14% in the 2080 series. On the other hand, relative humidity levels predicted by CCWorldWeatherGen tool were on average around 11%-15% lower than the levels predicted by Meteonorm in each series. Other parameters such as the dew point, wet bulb temperature, radiation levels, sky cover, illumination levels, wind speed and direction showed variable disagreements between the two sets, although the average differences were around 0%-2%.

Thus, this comparison has shown a close proximity between the two tools, given that different calculation methods were used.

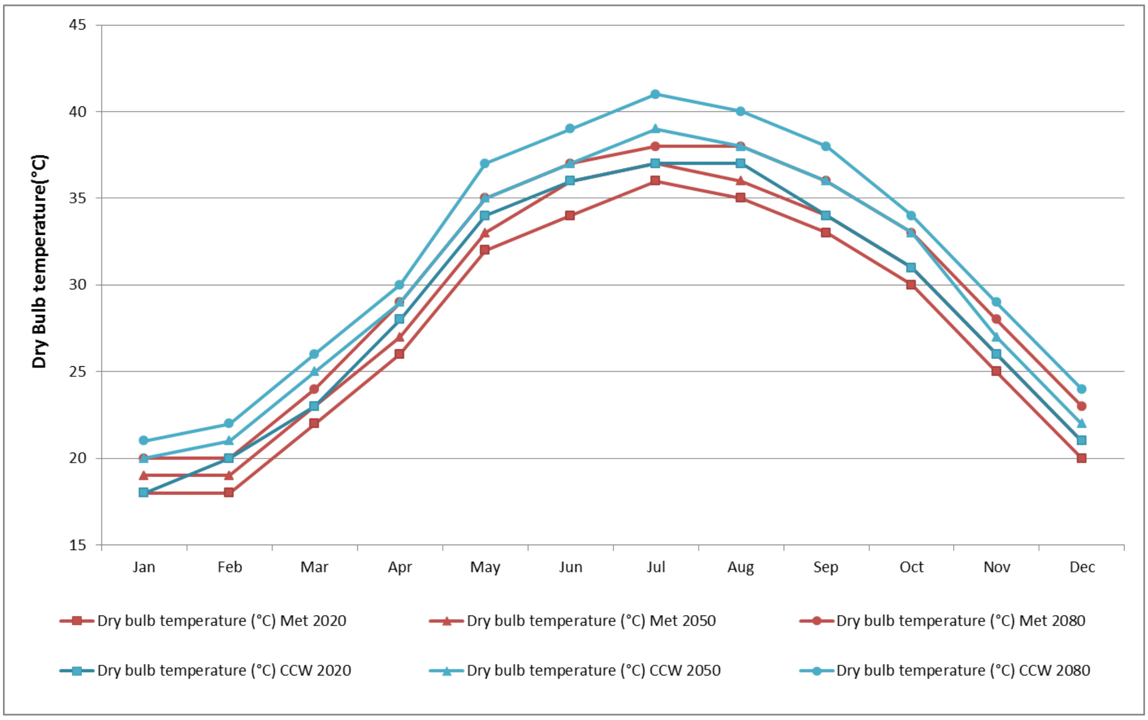


Figure 4-3 Average monthly dry bulb temperature for future weather scenarios

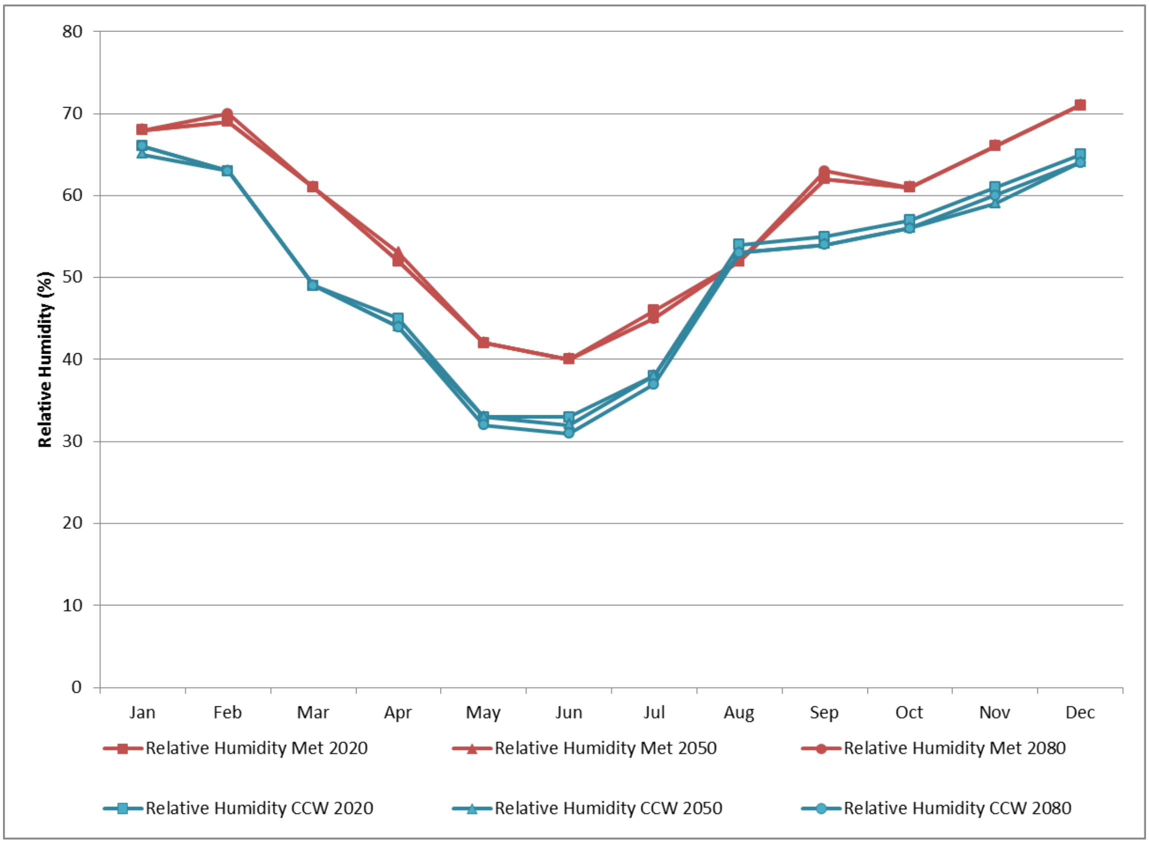


Figure 4-4 Average monthly relative humidity for future weather scenarios

4.3.2 Occupancy schedules and profiles

Occupant behaviour has been considered to be a complex element to quantify in the built environment. Many studies have traced occupancy patterns and their influence on energy use or their thermal comfort satisfaction levels through post-occupancy studies. It has also been found that occupant behaviour is one of the most challenging aspects to predict in the design process. However, despite the unpredictable pattern of occupant behaviours, including their impact in the built environment is unavoidable (Hong et al., 2016; Yan et al., 2015).

Occupancy schedules and profiles are an essential part of the input process to complete a building performance analysis, as required by most BPS tools. In addition, schedules for lighting, cooling and household equipment are equally important to estimate the internal gains in any given space. In Passivhaus buildings, internal gains are included as a means of passively heating a space in cool, moderate climates (Passepedia, 2015). Conversely, in hotter climates, internal gains need to be considered to aid in sizing the cooling system.

For computer modelling, the villas, the PHV and the STV, were estimated to be occupied by four family members, residing in the house mostly after work hours, i.e. from 6.00 pm until 9.00 am the next day. The cooling set point temperature was designed to be 23.5°C in all inhabitable spaces, with an ON/OFF controller. The lighting schedules were associated with the occupancy hours. Schedules for household appliances, such as washing machine, dishwasher, home entertainment, cooking, freezer, etc., were similarly estimated based on the occupancy pattern. Internal gains were included based on the number of people occupying the space, the type of appliance used and lighting systems.

4.4 Performance Indices

Performance indices have been used in research to evaluate the performance of buildings. A recent review paper presented a number of indices commonly used within research practices. The paper highlighted that these approaches may help in reducing the performance gap found between the predicted and the actual performance of buildings. Indices related to actual energy use and thermal comfort were grouped and defined in the study with the focus mainly on occupancy influence. This paper targeted designers and decision makers to attain an informed choice when faced with the evaluation process for a given project (Guerra-Santin and Tweed, 2015b).

In this study, a number of indices were used to evaluate the performance of the Passivhaus project in Qatar. IES-VE was mainly used to predict the energy consumption, thermal comfort and the thermal envelope performance of the Passivhaus villa and the standard villa. The results were obtained through the VistaPro module analysis tab under the energy section of the application set in IES-VE. The energy consumption was predicted for the HVAC system, lights and equipment in both villas. Additionally, the energy generated through the photovoltaic panels mounted on the roof of the Passivhaus villa was included and indicated as a negative energy output by the software.

The measurement of the thermal envelope performance of the villas was carried out by eliminating the effect of the cooling system in the two houses (disabling the cooling option). This indicator provided a measure of the effectiveness of the Passivhaus villa's extensive insulated shell. A comparison of the indoor temperature maintained without active cooling in both houses was analysed for all days of the year. To further understand how well the two shells operated without cooling, the extreme outdoor temperature was also considered in the analysis of the thermal envelope performance.

Additionally, a number of thermal comfort measurements were examined, which included the PMV index and the operative temperature and indoor relative humidity levels in the houses. The next section will cover in more detail the thermal comfort measurement aspects used in this research.

Finally, to validate the results predicted by IES-VE, on-site measurements were used in this study with the focus on energy use and thermal comfort. The importance of including actual measurements, as indicated earlier in this research, is because they aid in understanding the actual performance of buildings and bridge the performance gap indicated by a number of scholars. More details will be given in the last section about the process undertaken to obtain the on-site measurements and the tools used in the process.

4.5 Thermal Comfort Models

Thermal comfort has been defined as "*the condition of mind that expresses satisfaction with the thermal environment*" (Olesen and Parsons, 2002, pg. 460) . Factors affecting thermal comfort are categorised into three main groups (Szokolay, 2008):

(1) environmental factors, which include air temperature, air movement, humidity and radiation;

(2) personal factors, which include metabolic rate, clothing, state of health and acclimatisation;

(3) other contributing factors, which include food and drink, body shape, subcutaneous fat, and age and gender.

Given the various number of factors affecting thermal comfort, a universal thermal comfort index is not easily attained. A number of studies since the 1900s have been carried out to predict thermal satisfaction. Fanger's heat-balance thermal model is one of the most widely used measures. It is based on the thermal sensation of individuals in a controlled climatic chamber. The Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) are two indices derived from chamber experiments, and are frequently used by researchers around the world to predict and measure thermal comfort. Additionally, the two measures are frequently applied in BPS tools to measure thermal comfort in buildings (Attia and Carlucci, 2015; Rupp, Vásquez and Lamberts, 2015). Although there is wide acceptance of the PMV and PPD indices, many have argued that the results obtained through the PMV have shown under- or over-estimation of thermal sensation, especially in naturally ventilated buildings. Surveys carried out in naturally ventilated buildings have shown a discrepancy between the predicted PMV and the actual thermal sensation. Thus, the adaptive thermal comfort model was introduced (Becker and Paciuk, 2009). Furthermore, a number of efforts have been recorded that used different indoor variables to express thermal comfort in the built environment. Examples include the use of graphical charts, such as Givoni's building bioclimatic chart, and the Passivhaus graphical thermal comfort chart.

4.5.1 Steady-state thermal comfort and the PMV

The steady-state model was developed by Fanger based on a series of experiments carried out in controlled chambers. Environmental factors affecting thermal comfort, such as air and mean radiant temperature, relative humidity and air movement, were maintained fixed at pre-assigned levels, while personal factors such as clothing and metabolic rates were varied. Based on the findings from the experiments and the heat-balance equations, the PMV and the PPD models were developed. Many researches argue that the PMV/PPD are only suited for measuring thermal comfort in steady-state conditions. This refers to sealed buildings that are mechanically heated and/or cooled where occupants have no or very limited control of the indoor environment, although, in a recent review on human thermal comfort in built environments, it was indicated that the PMV model had also been used for non-air-conditioned buildings in warm climates (Rupp, Vásquez and Lamberts, 2015).

According to standards such as ASHRAE Standard 55 and ISO-7730, the PMV was used to predict the thermal vote of occupants by using a thermal sensation scale. The thermal sensation of the occupants in a given space is based on a 7-point scale representing the following votes: (-3.0) cold, (-2) cool, (-1) slightly cool, (0.0) neutral, (+1.0) slightly warm, (+2.0) warm and (+3.0) hot. Additionally, according to European Standard EN 15251, thermal comfort levels can be represented by categorising building types and assigning the relevant PMV according to Fanger's model, in addition to acceptable indoor temperatures for mechanically cooled and naturally ventilated buildings. For instance, based on the EN 15251 standard, a newly constructed, actively cooled building is expected to achieve a PMV level between −0.5 and +0.5 (Attia and Carlucci, 2015).

In this study, IES-VE was used to estimate the PMV. IES-VE uses the ASHRAE Standard 55 calculation methodology to predict thermal comfort, including air temperature, mean radiant temperature, dry-resultant and surface temperatures, relative humidity, PPD and PMV. Inputs in IES-VE were limited to the nominal design air speed, clothing level and activity level (metabolic rate). The following design assumptions have been made: (1) the nominal design air speed was limited to 0.15m/s, although well-designed Passivhaus buildings achieve indoor air speeds lower than 0.1m/s (Hopfe and McLeod, 2015). However it should be noted that mechanically cooled buildings may be subject to higher air speeds. According to ASHRAE, thermal comfort levels could be attainable at air speeds not exceeding 0.2 m/s. Yet, an increase in air speed above 0.2 m/s may result in better indoor conditions especially if the air temperature is high (ASHRAE, 2013); (2) summer clothing insulation was estimated at 0.5 Clo, with an activity level of 90 W/m^2, and (3) the winter clothing insulation was increased to 1.0 Clo, with the same activity level based on clothing and activity schedules (Parsons, 2003). The PMV was calculated for the inhabitable spaces only in both houses as they were the air-conditioned spaces of the villas.

An initial aim of the study was to compare the PMV with the actual occupant thermal sensation through a post-occupancy survey; however, due to the limitations mentioned at the start of this chapter, a post-occupancy study was not possible.

4.5.2 Adaptive thermal comfort

The adaptive thermal comfort model was established as a response to the limitations the steady-state PMV model encountered for naturally ventilated buildings. Field studies and regression models were carried out in naturally ventilated and mixed mode buildings to develop the adaptive model.

According to the adaptive thermal comfort model, occupants are more interactive with the indoor environment as they can freely adapt to change their thermal sensation. Three aspects are included in the adaptive model, which according to Rupp, Vásquez and Lamberts (2015) have not been fully considered in the steady-state model – psychological comfort aspect, behavioural aspect and acclimatisation. Occupants' indoor satisfaction is dependent on the outdoor conditions. Studies in hotter climates have noticed that occupants showed a higher level of thermal comfort satisfaction than might be expected given the warm to hot outdoor conditions.

The other factor evident in the adaptive model was that the occupants had more choice to operate windows, fans or blinds or even change their clothing level to achieve thermal comfort. Finally, occupants learnt to adjust or acclimatise to the conditions in which they were situated and consequently accept their indoor environment (Rupp, Vásquez and Lamberts, 2015).

The adaptive model according to ASHRAE Standard 55 is a function of indoor operative temperature and the mean monthly outdoor temperature (see Figure 4-5). It should be noted that the adaptive thermal comfort model provides a wide range of acceptable operative temperatures ranging from around 17°C up to almost 32°C, depending on the mean outdoor temperatures.

According to the climate in Qatar and the assumptions made in the villas, the possibility of applying the adaptive model was limited in this study for several reasons. First, due to the climatic conditions in Qatar, which are hot and dry most of the year, the possibility of utilising natural ventilation in the villas for much of the year was ruled out.

Secondly, the diurnal temperature variations were low and night ventilation was also not attainable. Finally, due to frequent dust-laden wind gusts in the area during the cooler months, opening windows was not a feasible option. Thus, the buildings were assumed to be mechanically cooled and ventilated most of the year.

Additionally, according to the Passivhaus standard thermal comfort criteria, the indoor temperature should not rise above 25°C for more than 10% of hours in a given year in naturally ventilated buildings, and in mechanically cooled buildings the cooling systems should be sized to achieve thermal comfort according to the Passivhaus standard all year round.

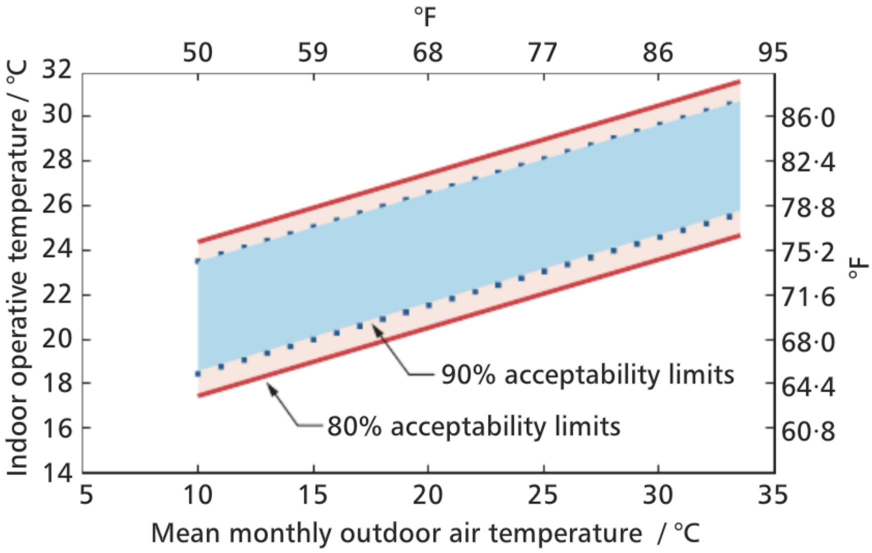


Figure 4-5 Acceptable operative temperature ranges for naturally conditioned spaces (CIBSE, 2014)

4.5.3 Other thermal comfort measurements

A number of graphical representations have been used to describe thermal comfort zones in the built environment. They normally incorporate the most influential factors affecting thermal comfort, "the environmental factors", which include indoor temperature, relative humidity, operative temperature, etc. The first well-known chart was introduced in the 1950s by Olgyay, and is mainly known as the bioclimatic chart. The chart included a graphical representation of two variables, the dry bulb temperature and the relative humidity levels, with a comfort zone marked by an aerofoil shape. Other considerations in the chart included air movement and radiation, which were represented by curved and straight lines allowing an extended comfort zone (Szokolay, 2008). Another comfort chart is the building bioclimatic chart. According to Attia and Carlucci (2015), Givoni's building bioclimatic chart, as opposed to Olgyay's bioclimatic chart, incorporated indoor variables to express the thermal comfort zones. Also, the chart was developed based on field measurements in residential buildings. Two comfort zones were marked in the chart relating to the expected comfort levels during summer and winter months (Attia and Carlucci, 2015). This chart has gained widespread acceptance and has been used as the basis for developing psychrometric charts used in a number of applications, such as Climate

Consultant and IES-VE, to express thermal comfort in buildings (McLean et al., 2011; UCLA, 2016).

A similar graphical representation is used by the Passivhaus Institute. The graph, which will be referred to as Schnieders' comfort chart, was used to assess thermal comfort in Passivhaus buildings in a number of reports and studies presented through the Passivhaus institute (Schnieders et al., 2012; Schnieders, Feist and Rongen, 2015). The chart was used to assess thermal comfort in occupied spaces. Annual hourly operative temperatures and successive relative humidity levels were plotted against each other in a graphical representation. A central internal comfort zone was represented by a shaded area containing operative temperatures that ranged between 20°C and 25.5°C. The acceptable relative humidity levels indicated by the chart were around 30%-70%. Additionally, an extended comfort zone was also included to allow for an additional increase of indoor operative temperatures – it was highlighted in a lighter shade in comparison to the inner comfort level zone (see Figure 4-6).

In this research, Schnieders' comfort chart was incorporated in order to follow a similar approach as that embraced by the Passivhaus Institute to indicate thermal comfort in occupied zones. The hourly annual operative temperature and relative humidity levels were obtained through IES-VE for all the occupied spaces in the two villas. This was achieved by increasing the reporting intervals to 60 minutes in the Apache simulation module. The results were later extracted to Microsoft Excel to graphically illustrate the variables using the scatter plot chart to further assess the thermal comfort in the spaces. The process was similarly repeated for the future time series to execute a comparative analysis between the different scenarios.

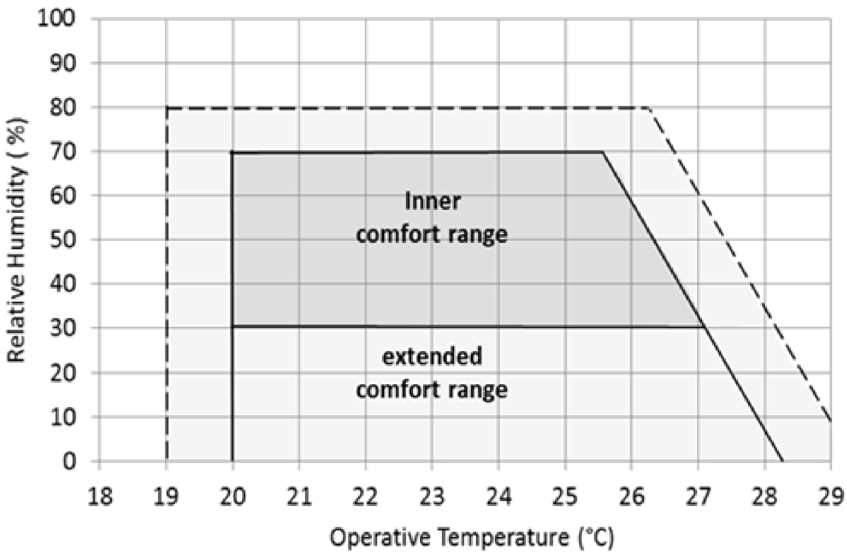


Figure 4-6 Schnieders' comfort chart (reproduced from (Schnieders et al., 2015))

4.6 On-site Measurements

Through the literature review it was demonstrated that actual on-site measurements provide a means of bridging the performance gap, which was identified through a number of empirical and field studies. A wide variety of tools could be used to perform on-site measurements depending on the indicators to be measured, the type of data to be collected, the type of buildings and the overarching aims of the investigation itself.

In a recent review (Guerra-Santin and Tweed, 2015b), data collection methods and techniques were grouped and presented to achieve an accessible single resource that showcased in-use monitoring in practice. The review referred to a number of tools that could be used to assess the performance of buildings in three main categories: energy, thermal comfort and building operation. Within each category a number of methods and tools were presented. According to Guerra-Santin and Tweed, energy performance could be measured using energy readings, high-frequency energy loggers or building management systems (BMSs). Energy readings were perceived as the easiest and most convenient and accessible method. The readings could be recorded either through existing meters or sub-meters. The purpose of investigation identifies the scope of the measurement; it could be recorded at the beginning and the end of the study, or at regular intervals during the study. The recordings are directly accessible through the meter observations and/or through the energy bills. High-frequency logging and BMSs provide more information related to the energy use, such as time-related energy use. Both tools could be used when a more detailed and lengthy investigation is required. High-frequency logging could additionally be coupled with other building performance indices such as thermal comfort and building performance.

Thermal comfort measurements, on the other hand, are attainable through the monitoring of indoor and outdoor variables and field surveys. The indoor thermal comfort and air quality could be measured either for a specified period of time at pre-set intervals, or alternatively at a specified point in time. Spot measurements are taken depending on the scope of the study to measure the indoor quality at a specific point of time, such as the time a survey took place. Indoor variables, including relative humidity, temperature, CO_2 levels, VOCs and air speed, could be recorded to produce thermal comfort-related parameters, such as calculating the PMV. Outdoor variables, including relative humidity, temperature, CO_2 levels, wind speed and direction, solar radiation and precipitation, are normally recorded to obtain thermal comfort using the adaptive thermal model. Difficulties found in using monitoring tools are related to locating the tools and safeguarding them from damage. Additionally, for measuring thermal comfort, questionnaires and surveys have been found to be the most straightforward option to undertake, although participant behaviours and modes have been found to be more subjective. Finally, building operation measurements can be used to assess detailed occupant behaviours such as water and heat use, frequency of operating doors and windows, movement in space or detailed appliance use. Sensors and monitoring devices in addition to other recording means such as log diaries, interviews and videos could be used in this category (Guerra-Santin and Tweed 2015b).

In this research, two performance categories were investigated, energy and the indoor thermal environment. Energy use, similar to the method presented in the latter-mentioned review, was obtained through readings from sub-meters installed in the villas. Based on the project’s target, sub-meters were incorporated early in the design of each building to enable monitoring. Three sub-meters were installed in each villa to display HVAC, light and small power use. In addition, three other meters were connected to inverters which displayed the energy generated through the PV panels in the PHV. A research specialist, who was a member of the project supervisory team in Qatar, provided three sets of sub-meter readings at irregular intervals. The first set represented around two years of energy use, while the other two sets indicated 15 and 20 days of energy use.

To estimate the monthly energy use, extrapolations were used using Microsoft Excel. Based on a linear regression between the HVAC energy use and the Cooling Degree Days (CDD), a regression equation was obtained and used to extrapolate the monthly energy use (see Appendix A). Daily CDD were acquired through an online degree days calculator which uses temperature data for the required location to calculate the CDD (Degree Days, 2016). Statistical analysis was used to calculate the monthly HVAC energy use from the sub-meter readings provided, by referring to the data sets, which were closely spaced. The extrapolated data were used to conduct a comparative analysis in order to measure the difference between the statistically estimated energy use and the predicted energy use obtained through IES-VE (no fuel conversion coefficients were required as the only energy source involved was electricity). The statistical approach adopted in this research was thought to be one of the best methods to overcome limitations in the data. The boundaries of using this method could be related to statistical errors in addition to possible original misreading, although with the limited number of readings the misreading errors may not be significant. Additionally, the choice of the CCD year and the cooling base temperature affects the calculation method and subsequently affects the estimated outcomes of the HVAC energy use, as temperatures differ from one year to another. It should be noted that the CDD acquired coincided with the same period the sub-meter readings were obtained for a cooling base temperature of 18°C.

Thermal comfort was assessed in the houses mainly by using the PMV index through IES-VE and Schnieders' comfort charts, as described in the previous section. However, to capture the actual indoor environmental conditions, data loggers were used to record the indoor temperatures and relative humidity levels of the presumably occupied spaces. Onset HOBO U12 data loggers (see Figure 4-7) were used as the monitoring tools due to the fact that they were the only available resources at the time the field study was conducted. The two-channel logger had a 12-bit resolution and was able to record up to 43,000 measurements (ONSET, 2016a). Due to the limited number of loggers, the external outdoor conditions could not be captured through monitoring equipment. Additionally, weather variables could not be acquired through the nearest weather station, although attempts have been made to contact the meteorological office several times in Qatar to obtain the required variables. To compensate for the lack of outdoor weather variables, the present day EPW weather file was used as a reference for the typical weather year to compare against the indoor recorded parameters.

Two monitoring periods were carried out in the villas. The first was during the summer of 2015 for five consecutive weeks, and the other for around 20 weeks between September 2015 and January 2016. The first monitoring period included all the occupied spaces in the two villas, showing the thermal environment during the hottest period of the year. The second logging period was limited to the living spaces in both villas, due to inaccurate measurements encountered during the first monitoring period. The length of the monitoring periods was associated with the physical presence of the author in the region. The main advantage of using data loggers in this research was the possibility of obtaining a significant amount of data without having to be actually physically present at the project. In addition, they provided synchronised readings of the thermal environment of each house. The only limitation associated with effectively using the data loggers may be related to their placement in the rooms. According to Guerra-Santin and Tweed, loggers should be placed in a central location in the space and should be hanging freely to avoid any radiation or emissions from objects or surfaces. In this case it was not feasible to place the loggers centrally, for the following reasons: (1) although the villas were not occupied they were occasionally visited by different groups, (2) the false ceiling was skimmed plaster boards and no readily available attachments were possible, and (3) in the possible case of loggers falling on the ground, there were no regular supervision routines carried out in the houses; this meant that no one would be able to put them straight back up or even notice that they had fallen. Therefore, it was safer to place the loggers on the interior walls using heavy-duty double-sided tape. The obtained indoor conditions were used in a comparative analysis between the actual and the predicted thermal environments in the two villas. This was used to provide an assurance regarding the predicted thermal comfort which was generated through IES-VE.

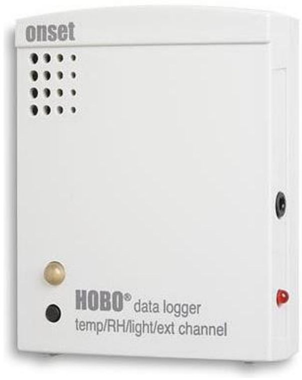


Figure 4-7 HOBO data logger (ONSET, 2016a)

4.6.1 Logger calibration

Data loggers are manufactured under controlled conditions to ensure that the readings obtained through them are as accurate as possible. Many loggers normally last a while before they need to be re-tested for accuracy (ONSET, 2016b). The data loggers used in this study were indoor loggers specified with an accuracy level of ± 0.35°C from 0° to 50°C temperatures and ±2.5% from 10% to 90% relative humidity levels.

To ensure that the data loggers were working accurately according to the specified accuracy level, a calibration process directly preceded the two logging periods. All loggers were placed in the same environment for several days to monitor the temperature and relative humidity levels (see Figure 4-8 and Figure 4-9). This calibration indicated that all loggers were functioning close to the specified accuracy levels, ruling out any possibility of erratic readings as a result of logger deficiency.

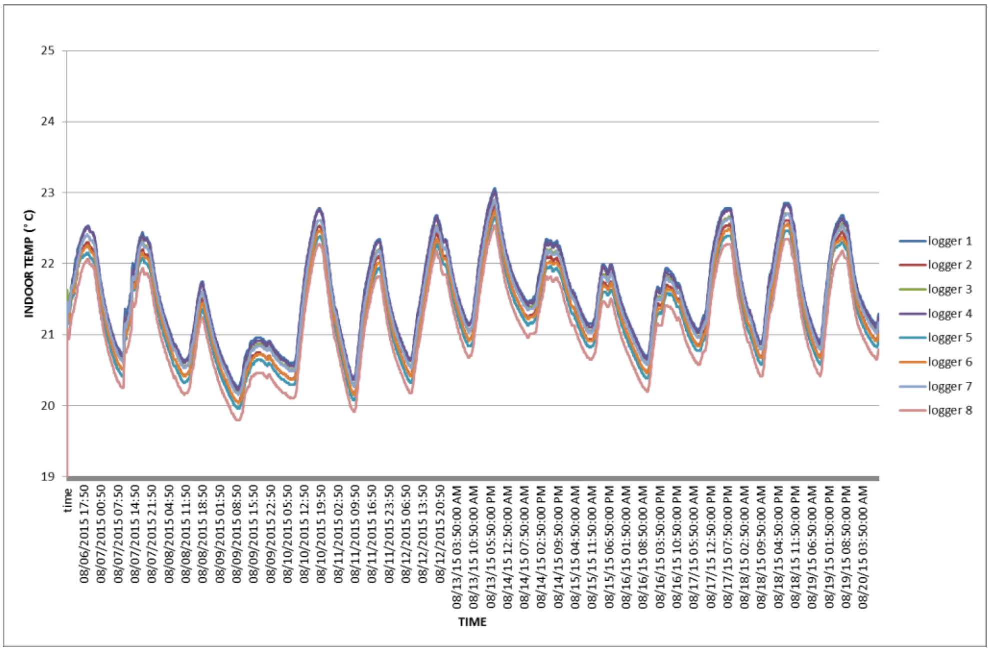


Figure 4-8 Temperature data logger calibration (first logging period)

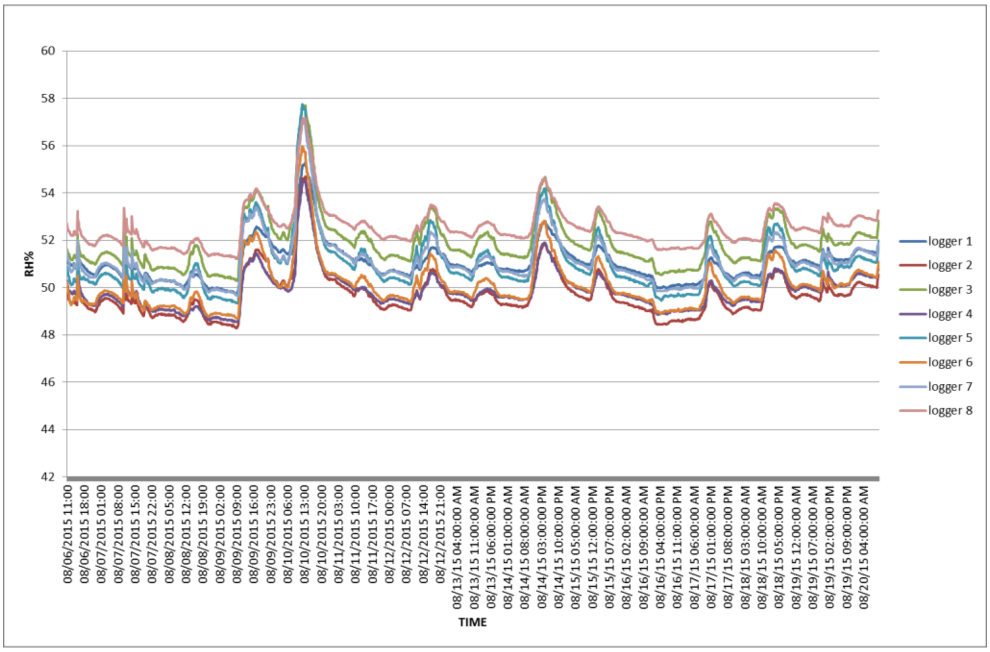


Figure 4-9 Relative humidity logger calibration (first logging period)

A similar calibration period was carried out for the second logging (see Figure 4-10 and Figure 4-11). The main purpose for repeating this task was to ensure that, in case inconstant data were recorded again, in comparison to the predicted data, the reasoning would only refer to an actual difference in the indoor thermal environment in one or both houses. This would therefore indicate errors in the simulation, either related to the assumptions made or in the inputs used for the project.

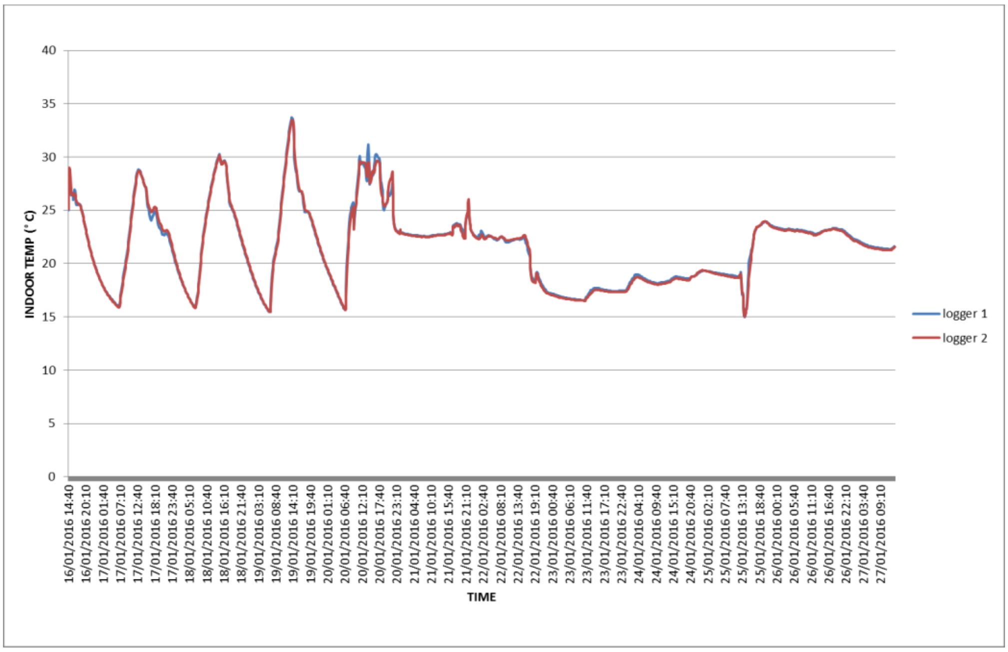


Figure 4-10 Temperature data logger calibration (second logging period)

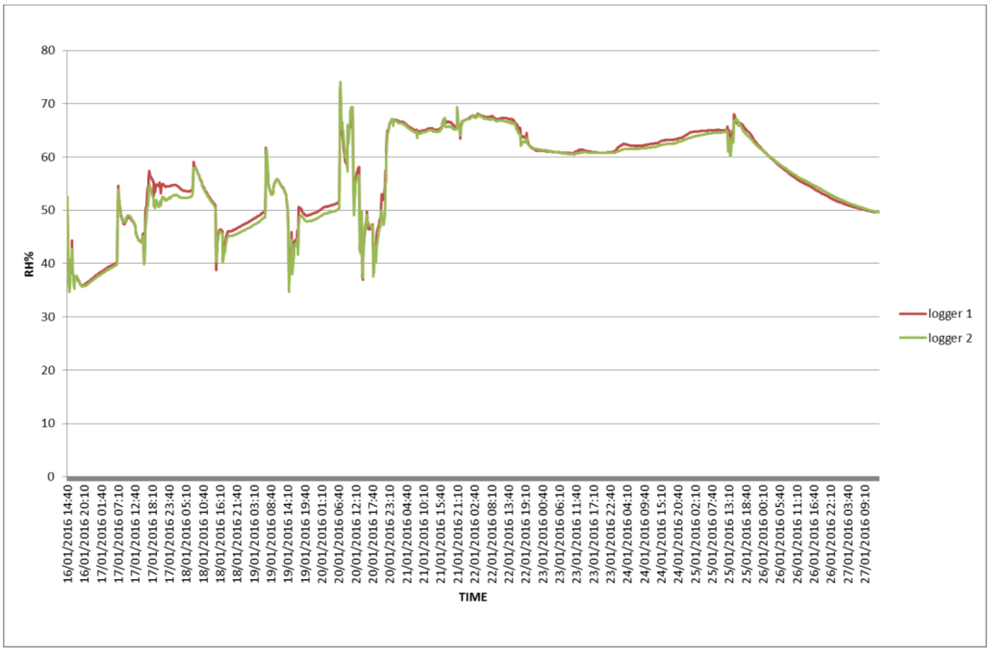


Figure 4-11 Relative humidity logger calibration (second logging period)

4.7 Summary

Recent research has shown that a performance gap can exist between a building's actual and predicted performance. Today, with advances in technology and with the emergence of energy-efficient standards and buildings, it has become of particular importance that buildings live up to their targeted standards. Additionally, with increasing calls on future-proofing buildings and mitigating the impact of climate change, buildings are expected to perform in accordance to their intended design derivatives.

Energy simulation tools are effective instruments used to virtually simulate the energy performance of buildings. They have aided designers and architects to achieve detailed data on the performance of buildings with fewer calculations and less effort, but unfortunately they are not error free. To overcome the possible errors associated with prediction and to further understand the actual use and performance of energy-efficient buildings, post-construction assessments were introduced. These have elevated the effectiveness of energy-efficient building to a different level.

Assessment procedures can be carried out during the various stages of the building cycle to provide assurance that the buildings are actually operating as/or close to designed assumptions. Architects and researches therefore can come to a better understanding on how buildings actually work. The assessment process, in addition to assuring that performance is in accordance to a certain benchmark, could also be used to rectify building elements, or to better design them for the future, and ultimately to ensure that a building continues to follow a certain benchmark (Babaei et al., 2015; Coakley, Raftery and Keane, 2014; De Wilde, 2014; Guerra-Santin and Tweed, 2015a).

In the current chapter, the assessment methods and the tools used to evaluate the Passivhaus project in Qatar were presented. Three indicators were used to assess the project: energy use, thermal comfort and the thermal envelope performance. The assessments of the three indicators were carried out by using a building simulation energy tool and on-site measurements. The indicators and tools used in the project were further described and discussed, examining all the integral elements related to each. Additionally, the limitations and challenges experienced during the project were highlighted with reference to the literature; this included the energy simulation tool used, the thermal comfort models and the on-site measurements recorded. Finally, a calibration of the monitoring tools was performed to assess the accuracy of the gadgets in accordance to their specifications.

The next chapter will focus in more detail on the Passivhaus project in Qatar. This is undertaken by providing a brief general background on the host country prior to a detailed description of the project and all its related aspects.

Chapter Five
Qatar's Passivhaus Project

5 Qatar’s Passivhaus Project

5.1 Overview

In 2013, Qatar launched the first Passivhaus project in the GCC region. The pilot project was initiated after discussions between the green building authority and a major private real estate development company in the country. Although the emergence of the Passivhaus project was surrounded with great publicity in Qatar, it seems that even neighbouring countries, let alone different parts of the world, were not fully aware of the existence of such a project.

This chapter, therefore, aims to reveal the story of the Passivhaus in Qatar. Passivhaus buildings are identified as ultra-low energy buildings that consume the least amount of energy and that provide a comfortable indoor environment. As presented in the first part of this study, a number of studies have evaluated Passivhaus buildings in different contexts; in addition, the PHI has issued a number of reports that tackle the presence of Passivhaus buildings in different climates.

The ambitious Passivhaus project in Qatar exemplifies an opportunity for a real-scale performance assessment of a Passivhaus building in a hot and arid climate. The guidelines of the Passivhaus standard were followed in the design of the project with respect to climatic consideration and availability of building materials and workmanship skills. The project was announced in 2013 and has since been directly supervised by Qatar’s Green Building Council (QGBC).

A number of studies are currently being undertaken in the Passivhaus building: a GSAS and Passivhaus comparative analysis study and a photovoltaic performance study, in addition to this research, which is focused on the assessment of the Passivhaus villa in comparison to the standard villa and in accordance to the Passivhaus standards.

5.2 Qatar's Housing Stock

The development of the housing stock in Qatar has been documented in only a limited number of resources. According to Al-Buainain (1999), this may be due to the lack of a housing organising authority in the country until 1996. The housing benefits policy in Qatar can be traced back to 1964, when the first law was declared regarding housing for citizens on low incomes. Later, in 1977, another decree was issued related to housing for high-level officials in the country. Finally, in 2007, a third decree adjusted the regulations for housing benefits for all citizens in Qatar and repealed the previous decrees (AlMeezan, 2016b; Nagy, 1997). The early housing policies provided fully funded plots or even units for Qatari citizens. They were introduced due to the need to reconstruct the central area of Doha, and came as a response to the scarcity of housing at that time (Nagy, 2000).

Al-Buainain and Nagy agree on two common housing types in Qatar, which were funded by the government: the popular house and the senior staff's house. Al-Buainain added a third type, which he referred to as the intermediate house. Prior to the introduction of these government housing schemes, houses included an open-space yard with a number of rooms on one end, usually serving multiple purposes, such as sitting, sleeping, and storage (see Figure 5-1). Other functional spaces around the yard in the form of temporary structures could also be added for cooking, washing and as animal pens (Nagy, 1997) .

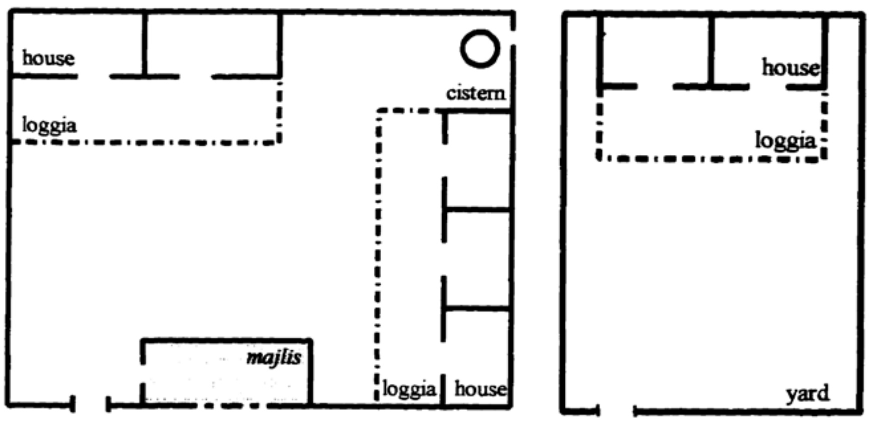


Figure 5-1 Open yard house forms (Nagy, 1997)

When the popular house type began to spread, it was designed mainly for disabled or elderly citizens, but was later also available to low-income and middle-class citizens. The built-up area of the smaller units was around $150m^2$, but the most common size, according to Al-Buainain, consisted of two to three bedrooms, a lounge and family living spaces, dining room, kitchen and associated services, such as toilets, storage and garage. The plot for a popular house can range from around 600 to above 900 m^2 (see Figure 5-2) (Al-Buainain, 1999). The most typical houses were normally one floor and designed as a series of adjacent, identical social houses. According to Nagy (1997), these houses were not regarded highly by the Qataris and were quickly replaced when an opportunity arose.

The senior staff houses, on the other hand, occupied an even larger plot of around $1200m^2$, and consisted of larger rooms and ample open spaces. Two guest quarters were commonly designed in these houses, one for male visitors and the other for female guests. In addition, the ground floor would normally accommodate the dining area and toilets. The upper floor would accommodate the private section of the house, which included the bedrooms and bathrooms, with an average of three to four bedrooms.

A new section was found in these houses. This included an external one storey section within the boundary of the house, consisting of one or more rooms. The external section was used for a number of purposes, such as a guest room, servants' quarters, laundry/washing room, storage, an external kitchen or even an external lounge. In addition, the senior staff houses still had external spaces dedicated for car parking, a garden and sometimes even a swimming pool within the boundary of the plot. The advantage of the senior staff house type over the other house type was that the owners of the former had more control over the design of their own house (Nagy, 1997).

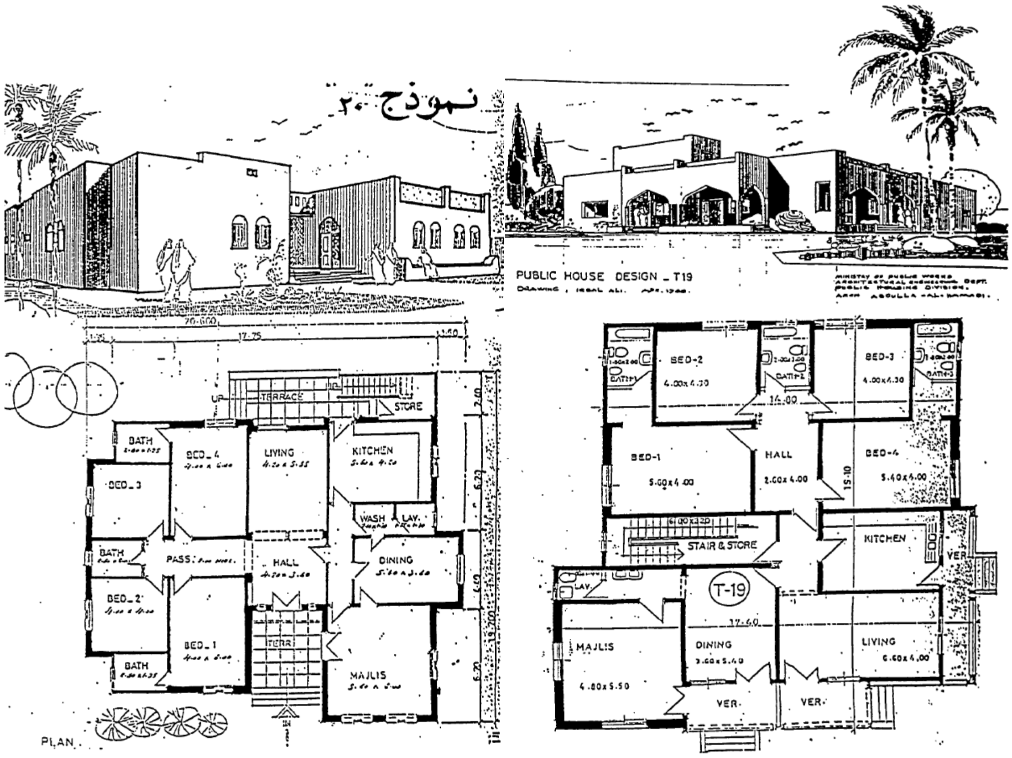


Figure 5-2 Popular house layouts (Al-Buainain, 1999)

Consequently, it could be argued that housing benefit schemes have contributed to the development of the housing stock in Qatar. Although public funds have been reduced gradually since their first emergence, accepted housing patterns seem to have become more defined. The senior staff housing type or, in other words, the villa-type form has spread widely in Qatar. This can be confirmed through the recent population and household census. According to the 2015 Qatari census, two building types are most dominant in Qatar – the villa and the public, or, as previously referred to, the popular house. Other residential facilities include other house forms such as, apartment buildings, and extensions. The census also indicated that the majority of Qatari citizens resided either in villas or in popular houses. Around 57% of Qatari families live in villas and 31% in popular houses, while only 4% reside in flats (MDPS, 2016).

5.3 Qatar's Energy Policy

Qatar initiated a number of regulating laws for buildings from as early as the 1970s. The regulations were not necessarily related to energy use, but rather were regulating the emergence of buildings and facilitating building planning permission for the different building types in the country (Mahgoub and Abbara, 2012). Energy related standards that included building envelope codes were first introduced in 1989 in relation to technical and architectural specification for new air-conditioned buildings. Enforced maximum U-values of 0.741 W/m^2°C for walls and 0.57 W/m^2°C for roofs, in addition to walls to window specifications, were included in the regulations (AlMeezan, 2016a; Awawdeh and Tweed, 2006). KAHRAMAA, the electricity and water authority in Qatar, reintroduced the building thermal insulation regulation in addition to other specifications, including HVAC requirement minimum criteria and lighting in the form of building guidance and regulation in 2010 and 2012. The building thermal regulation specified reduced U-values to 0.437 W/m^2°C and 0.568 W/m^2°C for roofs and external walls respectively (KAHRAMAA, 2016). Although such regulations have existed in Qatar and in the GCC generally, there is no evidence that they were actually being enforced in the building sector. In fact, a publication from Chatham House pointed out that poor enforcement of regulations was one of the obstructions to sustainability in the GCC (Lahn, 2013).

Nevertheless, Qatar has taken a number of steps to pave the way towards sustainability and the mitigation of greenhouse gas emissions. In 2007, Qatar established the National Climate Change Committee, which was responsible for establishing policies and offering guidance to other ministries in relation to the reduction of greenhouse gas emissions. In 2009, the Qatar Green Building Council was announced as an authority to promote green practices, knowledge and research. The Qatar Environment and Energy Research Institute (QEERI) was established in 2011 as a research facility to safeguard Qatar's future against water and energy shortages (QEERI, 2016). Additionally, Qatar has hosted a number of conferences and workshops related to climate change and energy efficiency. Most importantly, Qatar has outlined its sustainability and energy targets to source 20% of energy through renewable energy sources by 2040 and to reduce energy power generation by 7% by 2016 (Meltzer, Hultman and Langley, 2014).

Furthermore, Qatar has taken a number of measures to publish its first sustainability rating system. The Gulf Organization for Research and Development (GORD), in collaboration with the University of Pennsylvania and Georgia Institute of Technology, USA has established the first performance-based rating system for Qatar and the Middle East. The General Sustainability Assessment System (GSAS), formally known as the Qatar Sustainability Assessment System (QSAS), was announced after an intensive research and development phase. Over 140 rating systems and building standards from around the world were reviewed, out of which six globally established rating systems were further assessed towards the formation of the GSAS. BREEAM, LEED, GREEN GLOBES, CEPAS, CASBEE and the International SBTOOL were the six rating systems chosen for investigation by the development team. GSAS is built around eight pillars relating to sustainability in the built environment. Each category is then weighted differently based on its impact on the environment. Energy represents the category with the highest percentage weighting at 24%, and this category is further subdivided to include energy demand, the efficiency of the delivered energy, and the source of the fossil fuel and the associated emissions. This is then followed by the Water and Indoor Environment categories, which each represent 16% of the total weight. The water category involves water consumption, while the indoor environment category includes a number of factors related to the indoor quality, such as thermal comfort, natural ventilation and mechanical ventilation, indoor pollutants, natural and artificial lighting, and acoustic quality. The Cultural and Economics category represents 13% of the total weight and is composed of aspects related to identity, heritage and culture, in addition to support of the country's economy. Nine percent of the total weight is dedicated to the Site category, which comprises a number of subcategories, mainly related to the land value, its use, selection and development and planning. The Urban Connectivity and the Materials categories are weighed at 8% each. Urban connectivity involves factors dealing with traffic conditions, pedestrian pathways, proximity to amenities, light and noise pollution, sewer and waterway contamination, and public and private transportation. Finally, the Management and Operations category represents 6% of the total weight and encompasses features related to the operation and commissioning, such as energy metering, building management systems and recycling management.

Based on the weights and the scores earned against each subcategory, an accumulative score range of -1 to 3 can be obtained; -1 is considered as not acceptable, while scores from 0 to 3 are acceptable, according to GSAS. A score of 0 meets the baseline criteria in GSAS, while 1 is perceived as an acceptable level, 2 meets an improved level and 3 meets an optimum level. The minus (-) scale is used to ensure that the building performance is attained at the highest levels by trading-off the negative impact with a higher impact criterion. The GSAS covers a wide range of building schemes, which are categorised according to GSAS as classic schemes, unique schemes, construction schemes and operations. The classic scheme includes building types such as neighbourhoods, residential, commercial, educational and healthcare facilities. The unique scheme, on the other hand, includes facilities such as infrastructure, mosques, railways, light industry and sports facilities. A GSAG toolkit is used to accumulate the project's total points and display the level of certification to be obtained (GORD, 2016). The GSAS has been enforced in Qatar since 2012, where public buildings are expected to earn a 3 score on the rating system. Commercial buildings, on the other hand, are to incorporate the standard by 2016, while residential buildings are to comply by 2020. Applying the minimum GSAS standard is estimated to save around 30% in energy use compared to the conventional practice (Lahn, 2013).

5.4 Initiating the Passivhaus Project

Qatar, a member of the Gulf Cooperation Council (GCC) countries, is considered, alongside with the UAE, as leading GCC countries in the area of research, building energy and technology (Cooke, 2015; McGlennon, 2006; Willis, 2015). In 1995, Qatar established the Qatar Foundation, a private, non-profit organisation that offers support and programmes in three main areas: education, science and research, and community development (Qatar Foundation, 2016). The Qatar Green Building Council (QGBC) was founded in 2009 as a member of the Qatar Foundation. It is a non-profit, membership-driven organisation specialising in environmentally sustainable practices and development. QGBC hosts a number of events and organises workshops, lectures and accreditation training courses to increase awareness of green building. QGBC is not only limited to Qatar nationals, but is for the GCC as a whole. In addition, QGBC is a research-oriented organisation, which encourages studies related to Qatar's built environment. In 2013, QGBC announced the completion of the first Passivhaus experimental project in the GCC region (Hartman, 2013;

Siddiqui, 2013). This project could be viewed as one of QGBC's research-driven assets. The value of this project is not merely because it is the first in the region, but also because of the fact that a standard villa has been constructed alongside the Passivhaus villa, allowing physical and environmental performance comparisons to be made between the two. In addition, the two houses were intended to be occupied to permit additional post-occupancy studies (Bryant et al., 2013). The idea behind constructing this pilot project was a result of post-conference discussions between Dr Amato, the head of sustainability at QGBC, and Mr Al-Abdullah, Barwa Real Estate CEO. Both Amato and Al-Abdullah had attended a green building conference in 2012, and had since begun to show an interest in the Passivhaus standard. A visit to a Passivhaus building was the final trigger to bring the project to life. A team of experts led by the main project manager of QGBC was shortly formed; the team was composed of QGBC, the AECOM group from London, KAHRAMAA, the Qatar General Electricity and Water Corporation, BARWA real estate and other partners such as ALMCO and Qatar Solar Technologies (Alumco, 2014; MARHABA, 2013). A site in the Barwa City development was dedicated for the project. In addition, a team of experts was assigned throughout the design, construction and handling phases of the project from the involved parties (Melly, 2014).

According to the project team, five main goals were to be achieved:

1. A 50% reduction in annual energy consumption in the Passivhaus villa compared with the standard villa;
2. A 50% reduction in annual water consumption in the Passivhaus villa compared with the standard villa;
3. A 50% reduction in annual operational CO_2 emissions in the Passivhaus villa compared with the standard villa;
4. No more than 15-20% of additional capital construction cost to achieve the required Passivhaus villa performance compared to the standard villa;
5. The certification of the Passivhaus villa by either the Passivhaus Institute or a similar authority.

In addition, an ambitious monitoring and commissioning phase of the project was set up by the team in Qatar. This included the use of a Building Managing System (BMS) and a weather station. The BMS was designated to monitor the electrical, mechanical and indoor conditions of the two houses, allowing full access towards the assessment of the performance of the Passivhaus project. Furthermore, according to the initial proposal, two small families were to be accommodated in the experimental houses after a period of at least four consolidated months of monitoring without occupancy. The houses were to be occupied for a period of at least two years, with the families not being trained on how to operate the Passivhaus villa for the first few months. Later on, induction training was to take place, and further monitoring was then to commence. Unfortunately, due to sponsorship and property ownership issues, the two houses were never fully monitored or occupied as intended. Now, both villas are periodically visited by a number of interested bodies, such as researchers, students and individuals. Additionally, a number of studies were presented at QGBC's first conference in 2015 related to research undertaken in Qatar's Passivhaus project (QGBC, 2016).

Although the initial monitoring was not established by QGBC as intended, it should be noted that QGBC generously allowed the author access to the villas. This enabled the placement of the author's own data loggers in the houses so that some monitoring data could be collected.

The next sections will describe both villas in more detail, and the methods that were adopted for measurements in them.

5.5 Qatar's Passivhaus Project

5.5.1 Qatar's weather

Qatar peninsula, according to the Koppen-Geiger climate classification map (see Figure 5-3) is located in the arid desert hot zone (BWh). This zone is characterised by mean annual temperatures that are greater than 18°C, and with low precipitation levels of less than 250mm (Peel, Finlayson and McMahon, 2007).

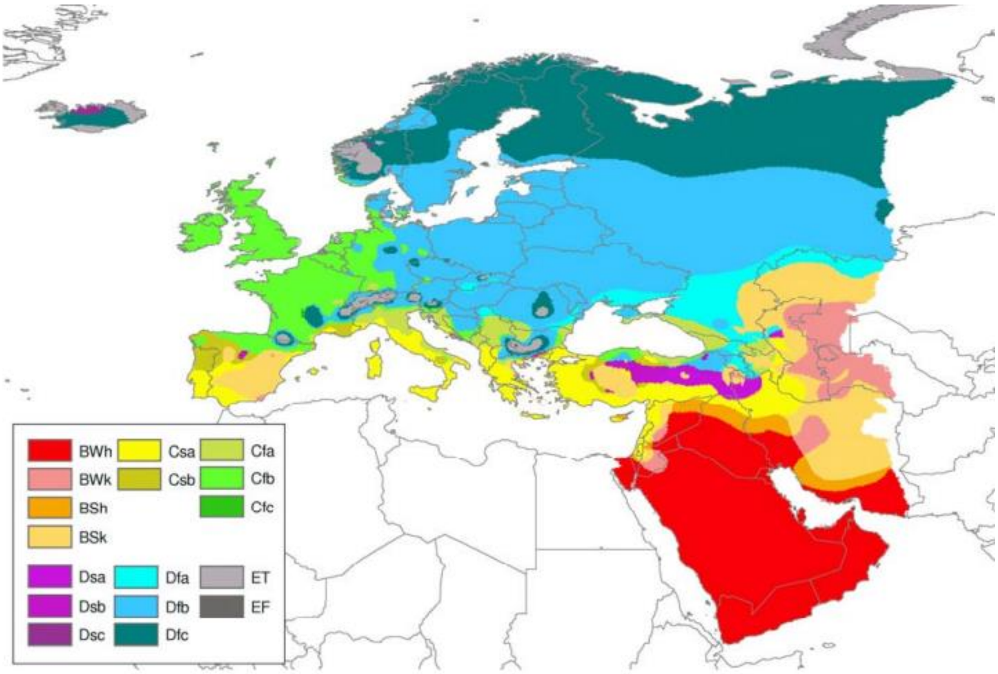


Figure 5-3 Climate classification for the region (Peel, Finlayson and McMahon, 2007)

Qatar's meteorology department (QMD) has issued a number of climatological reports (QMD, 2016), which include rainfall, air temperature and relative humidity. Both records of rainfall and temperature are based on data collected over a period of around 50 years (1962-2013). Relative humidity levels, on the other hand, are based on data collected over a period of 20 years (1990-2013). Based on Qatar's climatological norms, the average annual rainfall level is around 6.6mm. Rainfall in Qatar is normally experienced from October through to April, with the highest monthly average rainfall level of 18.6mm in March. May to September have shown an average monthly 0mm of precipitation, with the exception of May, which showed an average of 1mm of rainfall. Based on the historical data, the maximum recorded rainfall level was experienced in March 1995, when it reached 141.6mm. The average annual air temperature through the recorded period was found to be around 27.3°C. During the summer months, which are taken as May to September, the average air temperatures range from 31°C to around 35°C. The highest recorded air temperature was 50.4°C in July 2010. During the cooler months, from December to February, the annual average air temperatures range from 17°C to 19°C. The lowest recorded air temperature was in January 1965, when the temperature dropped to 3.8°C.

The months of March and April and October and November are considered the spring and autumn months respectively, and act as transitional months to the main two distinct seasons in the country, the summer and winter. The average annual relative humidity level is 61%, with the highest mean monthly average of 74% during December and January. The lowest monthly average is during May and June, when the relative humidity levels reach 45% (see Figure 5-4).

Qatar receives an abundance of sunshine – the annual average daily sunshine hours total is around 9.5 hours and the average daily horizontal global solar radiation is around 5.18 kWh/m^2/day.

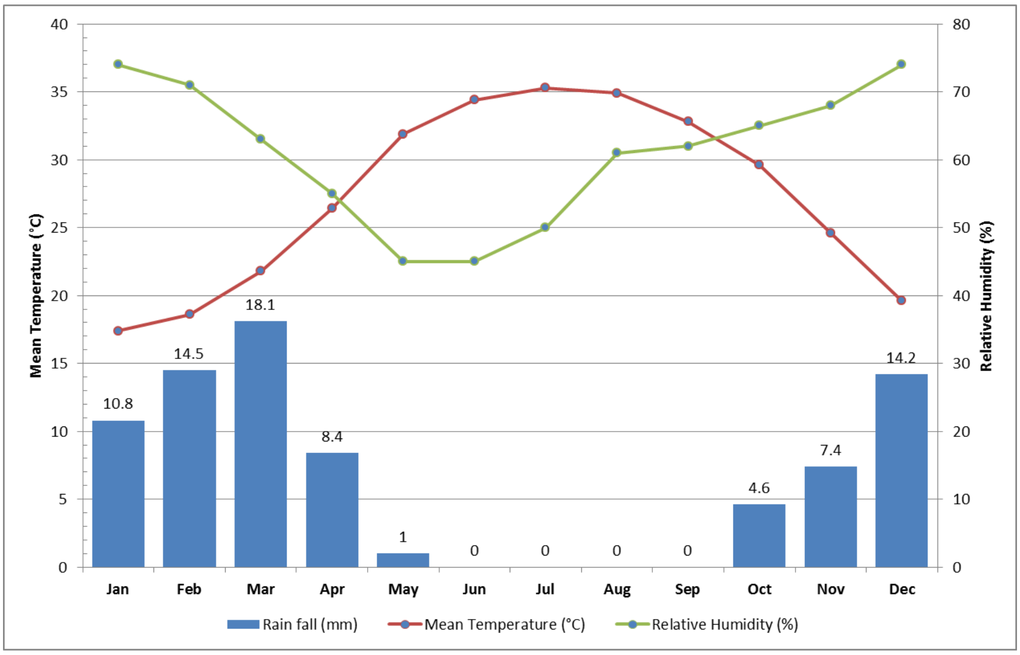


Figure 5-4 Average monthly rainfall, mean temperature and relative humidity (QMD, 2016)

5.5.2 The Passivhaus Villa

The Passivhaus pilot project in Qatar is composed of two villas, a standard villa (STV) built according to the one star on the GSAS scale and a Passivhaus villa (PHV). Both villas are similar in size, general layout and orientation (see Figure 5-5), but differ in their building materials and systems. The villas were each designed to accommodate a small family of three to four members, in a three bedroom, single storey house (see Figure 5-6). Although aspects of the dwellings relating to the Qatari life style were respected in the design of the houses, it might be argued that the properties may not represent a typical Qatari house. However, it should be noted that the purpose of constructing the houses was an experimental investigation. The design process was a joint venture handled by the QGBC in Qatar and the AECOM group in London.

Figure 5-5 Standard villa in foreground and Passivhaus villa

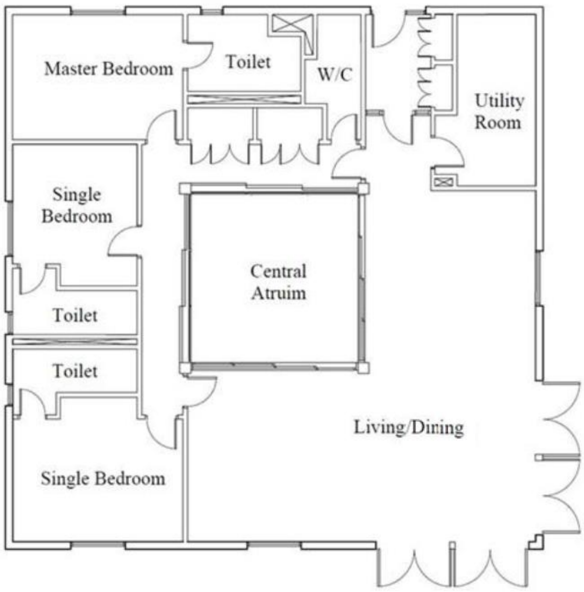


Figure 5-6 Typical villa layout

The design of the project respected the particular architecture of the region in a number of ways. Two main features were implemented in the design – the central courtyard and the colonnade system around the villas. Additionally, privacy aspects were addressed through the use of a decorative wooden panel that separated the private and public quarters of the houses, in addition to the use of separate entrances to the houses. The floor area of each house is around $200m^2$ and is composed of a central courtyard, two single bedrooms, a master bedroom and a living/dining space in addition to the supporting facilities.

The wide living room's double-glazed doors provide a sense of continuity to the outdoor green area, extending the interior space to the outdoor space through the shaded colonnaded patio leading to the landscape around the house. The villas are situated in a new development called Barwa city, which is located around 18 km south-west of the capital, Doha (see Figure 5-7).

Figure 5-7 Barwa city development location (Google Maps, 2016; Barwa, 2015)

The Barwa development is a mixed-use residential community that provides a sustainable living style for its potential 25,000 inhabitants. The city is designed to include around 6000 living units, along with all necessary amenities, such as educational, religious, commercial and recreational facilities. Furthermore, the project benefits from centralised air-conditioning and district cooling systems (Barwa, 2015; Waseef, 2016).

The Passivhaus villa (PHV) was constructed according to the German Passivhaus standards, aiming to achieve an ultra-low house with a highly articulated outer shell. The thermal bridge free building is characterised by an extensive insulation layer that secludes the ambient outdoor conditions from the interior by a 380mm polystyrene layer on its roof, walls and 200 mm on its slab. In addition, the glazed surfaces, which make up almost 25% of the outer surface, were installed as triple-glazed low-e units (see Table 5-1). The infiltration rate of the villa was minimised to be as close as possible to the Passivhaus standard. Additionally, the whole roof of the PHV is completely shaded by a 220m^2 photovoltaic (PV) panel array mounted on its top. The PV array extends beyond the roof boundary and provides shading for the living/dining windows. The highly airtight structure is ventilated through a high efficiency mechanical ventilation system. Furthermore, high efficiency lighting and cooling systems are installed in the PHV. In addition, a grey-water harvesting system was used in the PHV for toilet flushing and landscape irrigation.

The span of the square shaped PHV is around 14.7m, divided into three equal segments, each of around 4.9m on each side. The north-west façade of the PHV accommodates the 16.86 m^2 master bedroom, entrance lobby, utility room and toilets. The north-east façade is dominated by the 72m^2 living and dining space. Similarly, the living and dining space dominates the south-east façade, with an additional 15.9m^2 single bedroom. Finally, the south-west façade of the PHV accommodates the 11.57m^2 of the single bedrooms, toilets and the walls of the master bedroom.

The second largest space of the PHV is the central courtyard, which is around 24m^2 in area. Fixed and movable double glazing panels are used for the courtyard's full width glazed walls. Fixed panels overlook the corridors of the private quarters and are obscured by an Islamic motif wooden panel to provide privacy for those quarters. The movable glazed panels, on the other hand, open the living and dining space to the centre of the courtyard (see Figure 5-8). The central courtyard is covered with a double-glazed skylight fitted with an external controllable louvered shade.

A blower door test was performed to measure the airtightness level of the PHV; the main entry door was used to set the calibrated blower door. The outdoor conditions were recorded as sunny with clear skies and regular breeze. The HVAC and ventilation systems were switched off, while windows and doors remained shut. Through the pressurizing and depressurizing tests to ± 50 Pa the air tightness results revealed a 0.9 ACH in the PHV.

Figure 5-8 PHV interior (movable panels)

Table 5-1 PHV material and finishes

Type of finish/ Material	Location	Details
Floor slab material		
Concrete Raft Foundation	All areas	10-20 mm selected floor covering -50mm levelling screed -250 mm concrete raft foundation -1000 gauge polystyrene water vapor barrier -200mm extruded polystyrene thermal insulation layer - 75mm blinding concrete - 1000 gauge polythene thermal insulation - compacted fill or natural soil
Flooring finish		
Timber Flooring	Living & dining, bedrooms	Oak 20mm thick
Porcelain Tile	Toilets	Tiles 10 mm thick
Resin Floor	Lobby, utility room, kitchen, corridor	Thickness to match timber floor
Wall material		
Concrete Block Work	Kitchen, living & dining, bedrooms, lobby, utility room (toilet)	Internal face block work- 200mm solid, high-density non-load-bearing wall - external face 380mm thick rendered insulation (vapor barrier between insulation & masonry wall), (tile-finished internal face block work for toilets)

Table 5-1 continued

Type of finish/ Material	Location	Details
Wall finish		
Paint Finish	Living & dining, bedrooms, lobby, utility room, kitchen, corridor	Gypsum Board Paint Finish
Tile Finish	Toilets	Porcelain Tiles
Roof material		
Concrete Roof Slab	All areas	40mm deck paver on waterproofing roof finish- 380mm extruded polystyrene thermal insulation -waterproofing membrane -50mm creed 1% min slope-200mm concrete roof slab- 15mm plaster and paint ceiling finish
Ceiling finish		
Cement	Kitchen, living & dining	Rendered sand cement slab soffit
Paint	Bedrooms, corridor, lobby & around atrium	Plaster board skim + paint finish
Ceiling tiles	Utility room, toilets	600x600mm perforated alum. metal ceiling tile
External doors & windows		
Aluminium	Lobby	Powder-coated aluminium, single leaf, triple glazing with clear glass
Aluminium	Dining & living	Powder-coated aluminium, double-hinged door, triple glazing with clear glass
Aluminium	Atrium	Powder-coated aluminium, three sliding doors & one fixed screen, double glazing with clear glass
Aluminium	Bedrooms & living, toilets, kitchen	Extruded aluminium, PVDF-coated, triple-glazed, external semi-reflective tempered glass, hermitically sealed air gap, awning, and internal clear, tempered glass.
Aluminium	Atrium	Powder-coated aluminium, three fixed screens, double glazing with clear glass
Internal doors		
Timber	Lobby (hall, living)	Timber frame, single-leaf swing door with clear single-glazed panel and fixed, glazed panels on sides & above, (fixed glazed panel on above only for hall and living)
Timber	Utility, en-suite toilets	Timber frame, single-leaf swing door with translucent single-glazed panel and fixed, glazed panel above
Timber	WC (bedrooms)	Timber frame, single-leaf swing door with timber painted inset and fixed, glazed panels above (covered with timber screen for bedroom spaces only).

5.5.3 The Standard Villa

The standard villa (STV) was constructed according to the recently adopted sustainable assessment system in Qatar (GSAS). The house was constructed as one star on the rating system. This was achieved through the use of double-glazed windows for the external fenestration. In addition, thermal insulation of around 50mm was used for both the walls and the roof of the STV (see Table 5-2). Furthermore, the courtyard, in comparison with the PHV, was left open to the sky (see Figure *5-9*), although there were discussions afterwards about covering the void. The roof of the STV is unshaded, while a shade extends from the boundary of the roof to provide shading for the living space's large, glazed surfaces (see Figure 5-10). Standard, but not necessarily high efficiency installations and fittings were used in the STV, such as standard multi-zone split A/C units, lighting and home appliances. The size and orientation of all the rooms in the STV are similar to the PHV. The STV walls are composed of two layers of concrete blocks with a 50mm air cavity in between, acting as a thermal insulation layer. On the roof, on the other hand, a 50mm extruded polystyrene layer was used as the insulation material.

Similar to the PHV a blower door test was carried out to measure the air tightness level of the STV. Similar conditions and volumetric configurations to the PHV were assumed. The outcomes of the test revealed that the STV had an airtightness level of around 2.5 ACH.

Figure 5-9 STV central courtyard

Figure 5-10 STV external shade

Table 5-2 STV material and finishes

Type of finish/ Material	Location	Details
Floor slab material		
Concrete Raft Foundation	All areas	Selected floor covering -250mm concrete raft foundation -75 mm blinding concrete and 1000 gauge polythene water vapor barrier on compacted fill or natural soil
Flooring finish		
Timber Flooring	Living & dining, bedrooms	Oak 16mm thick
Porcelain Tile	Toilets, lobby, utility room, kitchen, corridor, kitchen	10-11 mm thick
Wall material		
Concrete Block Work	Kitchen, living & dining, bedrooms, lobby, utility room (toilet)	Internal face block work, 150mm solid, normal density non-load-bearing wall with external face block work 100mm, solid, normal density, non-load-bearing wall with 50 mm air cavity insulation (tile-finished internal face block work for toilet)
Wall finish		
Paint Finish	Living & dining, bedrooms, lobby, utility room, kitchen, corridor	Similar to PHV
Tile Finish	Toilets	Similar to PHV

Table 5-2 continued

Type of finish/ Material	Location	Details
Roof material		
Concrete Roof Slab	All areas	40mm deck paver -4mm elastomeric bitumen -50mm extruded polystyrene thermal insulation -50mm screed 1% min slope -200mm concrete roof slab -15mm plaster and paint ceiling finish
Ceiling finish		
Cement	Kitchen, living & dining	Similar to PHV
Paint	Bedrooms, corridor, lobby & around atrium	Similar to PHV
Ceiling tiles	Utility room, toilets	Similar to PHV
External doors & windows		
Aluminium	Lobby	Powder-coated aluminium, single leaf, double glazing with clear glass
Aluminium	Dining & living	Powder-coated aluminium, double-hinged door, double glazing with clear glass
Aluminium	Atrium	Powder-coated aluminium, three sliding doors & one fixed screen, double glazing with clear glass
Aluminium	Bedrooms & living, toilets, kitchen	Extruded aluminium, PVDF-coated, double-glazed, external semi-reflective tempered glass, hermitically sealed air gap, awning, and internal, clear tempered glass.
Aluminium	Atrium	Powder-coated aluminium, three fixed screens, double glazing with clear glass
Internal doors		
Timber	Lobby (hall, living)	Similar to PHV
Timber	Utility, en-suite toilets	Similar to PHV
Timber	WC (bedrooms)	Similar to PHV

5.6 Building Fabric Comparison

Since the beginning of civilisation, shelters have been the main structures providing a haven for people from outdoor conditions. The outer shell was always considered the first and most important barrier that separated the indoors from the outdoors, providing indoor comfort. A variety of examples can be seen around the world based on the climate and the available resources, such as caves, rammed earth houses, buried structures and igloos.

A number of studies have concluded that the outer building envelope is the main target for energy-saving improvements. Emphasis has been given to both the insulation of the exposed surfaces and the amount and specification of the glazed surfaces. In a recent review on the improvement of energy performance in buildings, the authors concluded that building envelopes, glazing and shading have been a persistent area of research throughout the reviewed period. In addition, the authors pointed out that, in recent years, attention has also been drawn to HVAC systems (De Boeck et al., 2015).

The Passivhaus standard, through its specific articulation of the outer fabric, has proven that the building fabric is of high importance in achieving energy savings and thermal comfort. All Passivhaus projects are characterised by an airtight, highly insulated outer shell with a high-definition glazed surface (Passepedia, 2015). The special fabrication of the outer layer of the PHV (see Figure 5-11) helps to create a highly insulated shell that maintains a very low thermal transmittance value (U-value). This value could be attributed to be the main factor that differentiates the PHV from the STV (see Figure 5-12). In addition to that, the PHV has been equipped with energy-efficient technologies leading to a better-than-anticipated performance in comparison to the STV.

The previous sections focused on the description of the PHV and the STV; this section will illustrate the thermal transmittance for both the opaque and glazed surfaces of the PHV and the STV (see Table 5-3 Opaque components and Table 5-4 Glazed components).

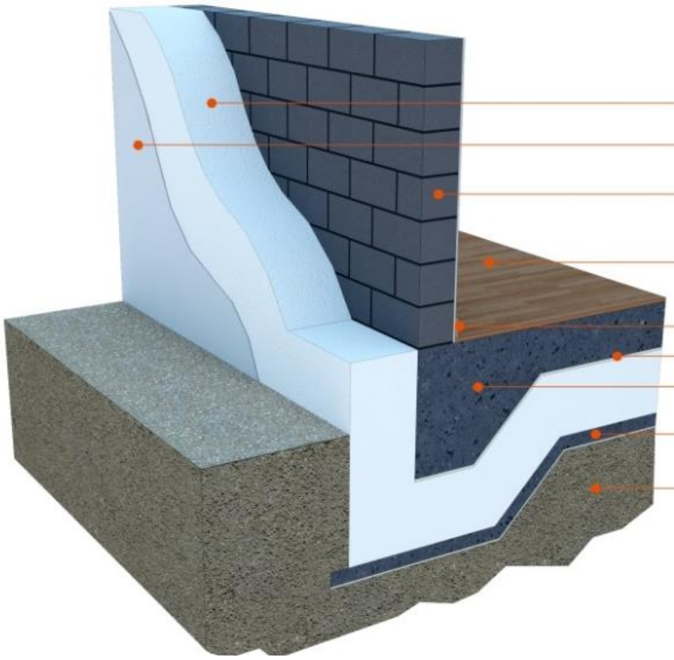


Figure 5-11 PHV external wall

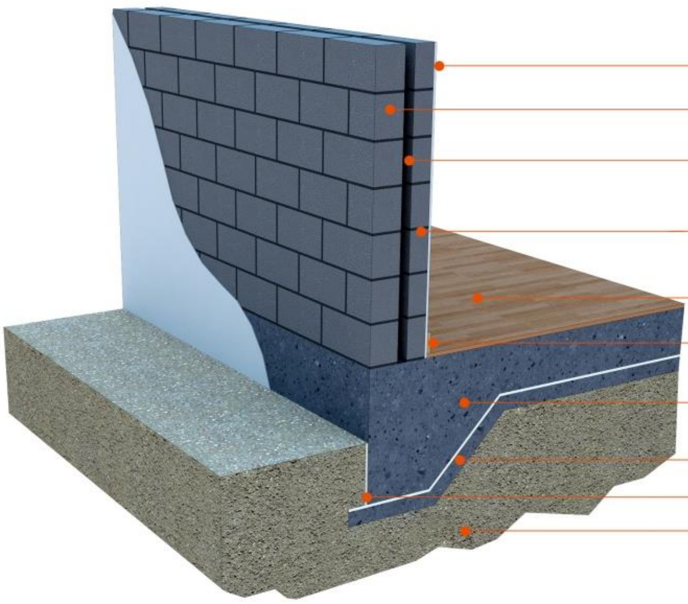


Figure 5-12 STV external wall

Table 5-3 Opaque components

Building Component	PHV Thickness (mm)	PHV U-Value (W/m²K)	STV Thickness (mm)	STV U-Value (W/m²K)
External wall	576	0.08	300	1.31
Internal partitions	120	1.73	120	1.73
Ground slab	2600	0.12	2950	0.50
Roof	580	0.08	300	0.30
Atrium roof	150	0.23	-	-
Atrium wall	-	-	120	3.20
Internal ceiling around atrium	110	2.28		
Wooden doors	40	2.19	40	2.20

Table 5-4 Glazed components

Glazing type	PHV U-value (W/m²K)	PHV U-value glass only (W/m²K)	PHV g-value glass only	STV U-value (W/m2K)	STV U-value glass only (W/m2K)	STV g-value glass only
External glazed living door	1.12	0.71	0.20	2.62	2.65	0.73
External glazed entrance door	1.49	0.71	0.20	2.59	2.65	0.73
Bedroom windows	1.09	0.71	0.20	2.62	2.65	0.73
Kitchen window	1.11	0.71	0.20	2.62	2.65	0.73
Toilet window	1.45	0.71	0.20	2.59	2.65	0.73
Sky light	1.27	1.02	0.21	-	-	-
Atrium glazing	2.39	2.25	0.74	2.62	2.65	0.73

5.7 Monitored Data

Predicting a building's energy performance has now become an integral part of the design process in many developed countries. A huge burden has been placed on the building sector to reduce greenhouse gas emissions and to mitigate climate change impacts. Building energy simulation tools are now largely used to predict the performance of buildings, and to ensure that they are energy-efficient. However, a number of researchers have pointed out that a performance gap is evident in buildings (De Wilde, 2014; Menezes et al., 2012). Inaccuracies in the predicted data are governed by the different parameters used to create the building model, such as the building materials, occupancy schedule, HVAC system and weather data. In addition, other possible errors related to the assumptions made by the designer, or even the impact of the occupant behaviour and the actual climate, can occur (Coakley, Raftery and Keane, 2014).

Therefore, in addition to using building simulation tools, researchers have incorporated other means to estimate building performance, including on-site measurements and surveys. These methods can be perceived as means of bridging the gap between the predicted and the actual building performance (Babaei et al., 2015).

Initially, the Passivhaus project was to have an extensive monitoring period of at least two years. During the first few months, the houses were anticipated to undergo a commissioning and calibration period to assess their energy and indoor comfort performance. Later, occupancy was scheduled and further monitoring was to take place. Unfortunately, the anticipated scientific testing experiment has not been accomplished to date, and subsequently the full set of data was never available for the project.

Alternative arrangements were made possible for this research. The Qatar Passivhaus team kindly provided three sets of metered energy use and PV generated loads. Although this may not provide enough evidence towards the actual performance of the villas, it has been used as an indicator towards their possible energy use. The three sets of data were broken into three categories – the small power, HVAC and lighting electrical use in the PHV and the STV, in addition to the PV generated load in the PHV. The three sets of data were recorded within variable time intervals, and were directly read from the electrical sub-meters installed in the two houses by a member of the QGBC team.

The first reading was taken on the 23rd of February 2015. It specified the energy consumption for almost two years, since the villas' first commissioning date. The second reading was recorded 20 days after the first reading, on the 15th March 2015, and the last reading was taken two weeks from the second reading, on the 29th March 2015 (see Table 5-5). The limited number of readings could be due to the fact that the project was inaccessible for the author, who was mainly based in Liverpool.

Additionally, due to the location of the project, which was almost thirty minutes' drive from the QGBC headquarters, recording the data was found to be not feasible and was not performed systematically and regularly by the team. In fact, it was only made available based on the author's request.

Table 5-5 Sub-meter readings

Meter reading (kWh)	First set		Second set		Third set	
	PHV	STV	PHV	STV	PHV	STV
Lights	2096	2515	2176	2613	2231	2684
Small Power	804	2066	824	2156	838	2211
HVAC	21697	78729	22007	79290	22294	79761
PV generated load	80086	-	82328	-	83684	-

In addition to the sub-meter readings, indoor condition parameters comprising indoor temperature and relative humidity levels were accessible for this project. After obtaining permission from QGBC, eight HOBO data loggers were placed in both villas (see Figure 5-13). The data loggers were placed in the spaces of the villas that were presumed to be occupied, the living space (LIV) and the bedrooms (M BR, BR 1, BR 2). The period of logging was limited to five consecutive weeks during the summer of 2015. The monitoring period was determined based on the author's presence in the region, and hence the possibility of fixing and dismantling the loggers.

The loggers were placed on the interior wall of the bedrooms and the false ceiling of the living room, in almost identical locations in both houses. The loggers recorded over 5500 readings, which included a calibration period for all the loggers. The whole logging period started from the 19th June 2015 and ran until the 27th July 2015, recording data at 10-minute intervals.

Table 5-6 illustrates the minimum, maximum and average indoor temperatures and relative humidity of the monitored spaces in both villas.

Table 5-6 First logging data

Monitored criteria	PHV				STV			
	LIV	M BR	BR 1	BR 2	LIV	M BR	BR 1	BR 2
Max Temp. (°C)	29.2	23.1	23.4	23.5	37.5	30.8	27.1	26.5
Min Temp (°C)	23.7	21.5	22.3	21.8	27.5	22.8	19.3	22.2
Avg. Temp.(°C)	26.2	22.1	22.6	22.5	32.2	26.7	22.2	23.2
Max RH (%)	53.2	65.4	63.9	58.2	47.2	68.2	53.0	60.3
Min RH (%)	40.1	46.4	45.2	42.3	15.7	22.8	27.6	27.3
Avg. RH (%)	44.7	57.4	55.2	51.9	24.8	39.5	42.9	41.8

A second period of data logging was required due to faults in the living room readings (see Table 5-7). The loggers were re-fixed from the 5th September 2015 until the 14th of January 2016, recording over 18,000 readings at 10-minute intervals. The placement of the loggers was altered to the interior walls of the two living spaces. The choice of positioning the loggers on the ceiling in the first attempt was based on finding a central location in the L-shaped living/dining space. This placement provided readings with very high indoor temperatures. The stack affect and temperature of the roof, in addition to the solar heat transmitted through the glazed surfaces in the living room, may have caused the increase in temperature (Khalfan and Sharples, 2016). The second logging attempt, even though the logger was positioned in one corner of the L-shaped living space, provided more reliable and close to predicted readings.

Table 5-7 Second logging data

Monitored criteria	PHV LIV					STV LIV				
	Sep	Oct	Nov	Dec	Jan	Sep	Oct	Nov	Dec	Jan
Max Temp (°C)	24.1	24.7	25.6	24.1	21.7	27.0	27.8	27.8	25.5	25.1
Min Temp (°C)	22.4	22.4	21.3	20.8	20.7	19.3	18.8	19.1	19.5	19.2
Avg. Temp (°C)	23.2	23.3	22.9	22.1	21.3	21.8	21.4	22.6	22.1	21.6
Max RH (%)	56.0	62.4	62.6	75.7	76.8	88.6	84.0	86.1	82.9	86.6
Min RH (%)	44.2	47.6	46.9	47.4	60.0	45.7	45.2	45.3	38.6	43.5
Avg. RH (%)	49.2	51.7	53.7	61.6	70.0	66.5	63.6	61.6	60.3	59.8

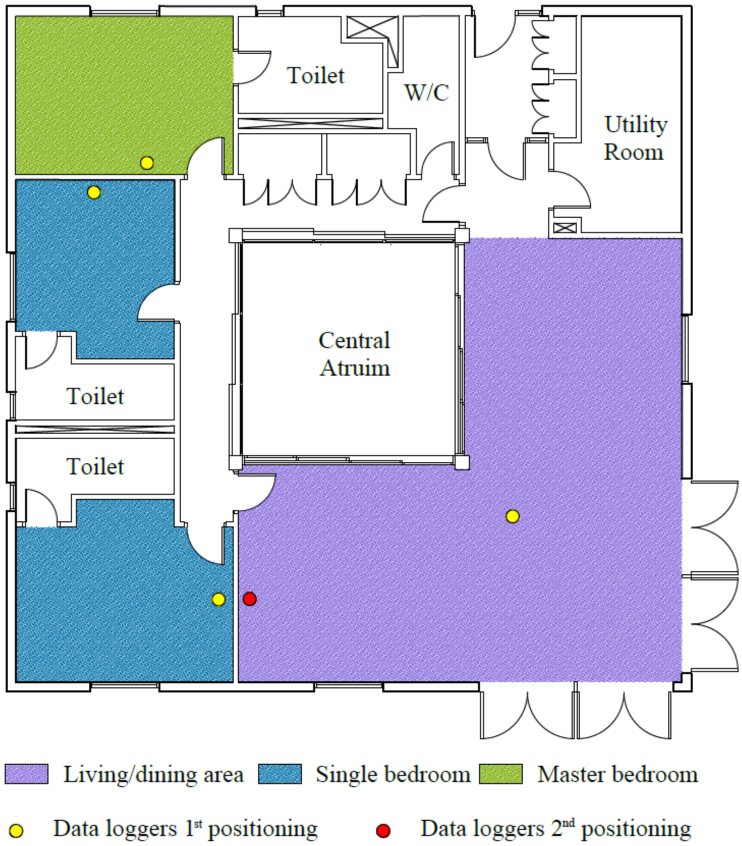


Figure 5-13 Data logger positioning

5.8 Summary

Buildings following the German Passivhaus standard have gained a great degree of attention in many locations around the world. This is evident through the number of buildings constructed according to this voluntary standard, which was estimated to be around 50,000 buildings in 2014 (Lewis, 2014).The standard has also been used as the basis to develop country/climate customised standards, which have even been named Passivhaus standards, such as the Passivhaus standards adopted in some of the Scandinavian countries and in the USA (Dequaire, 2012). This widespread and associated success caught the attention of a private developer and a green building organisation in Qatar. Qatar is one of the GCC countries that has experienced rapid growth in infrastructure and the built environment. Qatar has taken a number of steps to be recognised internationally for showing concern about the environment, especially given that it is one of the world's 10 highest CO_2 emitters per capita (World Bank, 2016a). Qatar was one of the first GCC countries to establish a National Climate Change Committee (in 2007) and a research institute specialising in the environment and energy, the Qatar Environment and Energy Research Institute (QEERI), in 2011. In addition to that, Qatar was the first GCC country to build a Passivhaus project in the region, in 2012, in an attempt to introduce an energy-efficient prototype building in the area.

This chapter has presented a detailed description of the Passivhaus project in Qatar. It started with a background description of the housing stock in Qatar, showcasing the most popular housing typologies that have been adopted in the country. This was followed by a brief recitation of the energy conservation policies and green practices in Qatar. The description of the Passivhaus was detailed in four sections. The first section included a narration of the Passivhaus story, by showcasing the parties involved in the project and the intended scope and aims as described by the Passivhaus team. This was followed by a detailed description of the project, first by describing the climate of Doha through variables obtained from the meteorological office website. Weather variables in Qatar have been collected for periods ranging from 20-50 years and are readily available on Qatar's meteorological website. The third section detailed the elements of the Passivhaus villa and the standard villa by describing the architectural and technical features of the building components. Finally, the monitoring process and the monitored data recorded in this research were described in the last section.

In the third part of the research, the findings and results of the assessment process undertaken in the Passivhaus project in Qatar will be presented through exploration of the three main indicators: (1) energy use, (2) thermal comfort, and (3) thermal envelope performance for the different timeline series.

Part 3

Analytical Review/Assessment

Chapter Six
The Performance of the Villas

6 The Performance of the Villas

6.1 Overview

Energy-efficient buildings are renowned for their high level of performance in comparison to conventional buildings. The emergence of energy-efficient models can be traced back to the 1970s, and was mainly triggered by the oil crises, which persuaded affected states to seek measures that ensured further energy savings in buildings. Since then, energy-efficient models have been continuously developed and evaluated to achieve better performance in the built environment. In developed countries, new technologies and targets have emerged to ensure that buildings sustainably continue to save energy throughout their lifetime. Various empirical and theoretical studies, therefore, are carried out to assess the performance of energy-efficient buildings and models. Additionally, energy targets have been set by most developed countries to sustain savings in energy for buildings of the future. A few decades later, a green movement had started to be noticed in the GCC countries. Within the last 10 years, green building councils and energy-efficient buildings started to be founded in the area, one of which was the Passivhaus project in Qatar completed in 2013. The performance of the Qatar Passivhaus project has been assessed through a number of indicators in this research based on the Passivhaus standard's strong principles. The German Passivhaus standard was promoted as a stringent standard capable of effectively reducing energy use while achieving high levels of thermal comfort. The carefully engineered building code revolves mainly around a highly insulated and airtight building fabric. Additionally, indoor conditions are maintained through the use of a mechanical ventilation system that ensures continuous delivery of fresh air to the inhabitable spaces, and the extraction of moist air from wet spaces. The Passivhaus standard has been applied to buildings in different regions around the world, many of which have been actually certified by the Passivhaus Institute in hot climate locations such as China, Indonesia and in parts of the United States of America; however, the Passivhaus standard is a newly adopted concept in the GCC. The first pilot project in the region in Qatar provided a promising potential to evaluate the actual performance of a Passivhaus building in the region.

The performance of Qatar's Passivhaus project is analysed in the following sections with the focus on energy use, thermal comfort and the thermal envelope performance. The first section reports the validation/calibration of the virtual model through comparison with field measurements consisting of sub-meter energy readings and recorded temperature and relative humidity levels. The following sections shed light on the current and the future predicted performance of the Passivhaus villa (PHV) and the standard villa (STV). Finally, the last section presents a parametric study that aims to bridge the performance gap between the STV and the PHV.

6.2 On-site Measurement Findings

As a response to the absence of monitored data, which was intended as an integral part of the scientific experiment in the Passivhaus project in Qatar, two alternative sets of measured data have been made available for this project. The first set was provided by the QGBC project team, comprising sub-meter readings from the two villas. The second set of data was obtained through data loggers, which provided recorded indoor temperatures and relative humidity levels of the inhabitable spaces in the PHV and the STV. In the next sections, comparative analyses between the predicted and the actual data collected will be demonstrated for each datum. The analytical comparison will provide assurance regarding the predicted performance of the villas, which was acquired through IES-VE software.

6.2.1 Sub-meter energy use

The Passivhaus project, as demonstrated in Part Two of this study, was an experimental project initiated by the QGBS and Barwa real estate. The project was intended to undergo extensive monitoring and post-occupancy studies, in addition to being a medium for a number of performance-related studies. Sub-meters were installed in the two villas to carry out the monitoring process; they were to be connected to a building management system (BMS) to allow full access to the energy and water consumption in the houses. Although a

BMS was never used in the project, fortunately the sub-meters provided some indicators towards the energy use in the villa, in addition to the PV generated energy.

The sub-meter readings were limited to three readings; the first reading was estimated to be taken two years after commissioning the villas. The two other readings were taken 20 and 15 days apart. Table 5-5 in Chapter Five showed the raw data that were provided by QGBC. The readings gave the small power, lights and HVAC system cumulative energy consumption in the PHV and the STV. A further analysis was needed to rationalise the data and to further assess the possible energy pattern in the houses. Due to the fact that the buildings have not been occupied by families, the usage patterns were relatively constant, as occupants' behaviours were excluded in this case. Additionally, based on the number of visits to the project and through the conformation of the QGBC team, the villas had been operated since commissioning, with both the lighting and the HVAC system in use, in addition to occasional usage of other equipment. It should be noted that a security guard was present in the project at all times, and mostly resided in the STV.

Table 6-1 illustrates the estimated actual energy consumption based on intervals between the recordings. Based on the statistically estimated energy consumption, a moderately consistent energy pattern could be observed through the different time intervals. The annual estimated energy use was compared to the predicted energy use in IES-VE for the two villas.

Table 6-1 PHV and STV actual energy use

Energy use (kWh)	365 days		34 days		20 days		15 days	
	PHV	STV	PHV	STV	PHV	STV	PHV	STV
Small Power	402	1033	34	145	20	90	14	55
Lights	1048	1257.5	135	169	80	98	55	71
HVAC	10849	39365	597	1032	310	561	287	471

A lower measured small power energy use was noticeable immediately, owing to the fact that there are no occupants in the villas. The measured lighting energy, on the other hand, showed close proximity to the simulated results. Most significantly, the HVAC consumption showed a slightly variable result: the PHV HVAC had been predicted to consume more energy, while less energy use was predicted in the STV in comparison to the measured data (see Figure 6-1 and Figure 6-2).

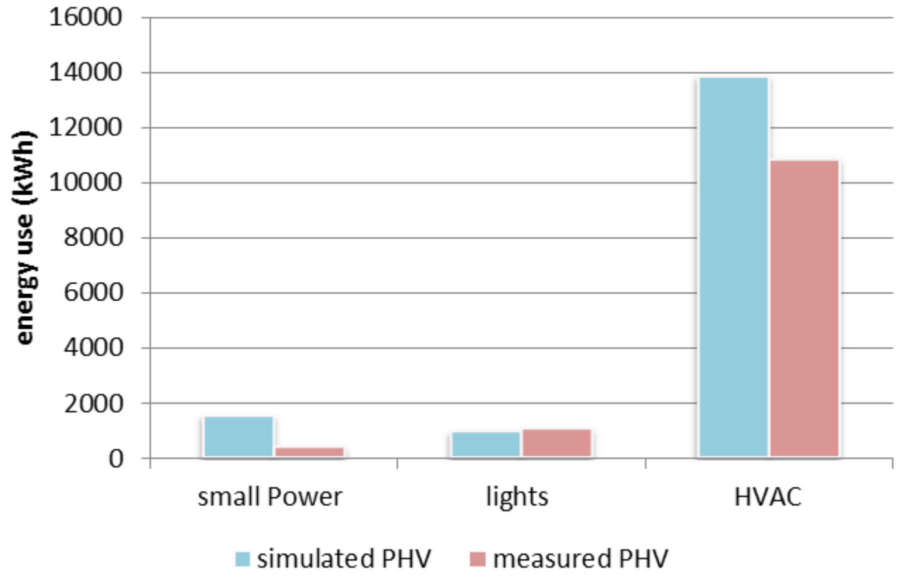


Figure 6-1 PHV simulated and measured energy use

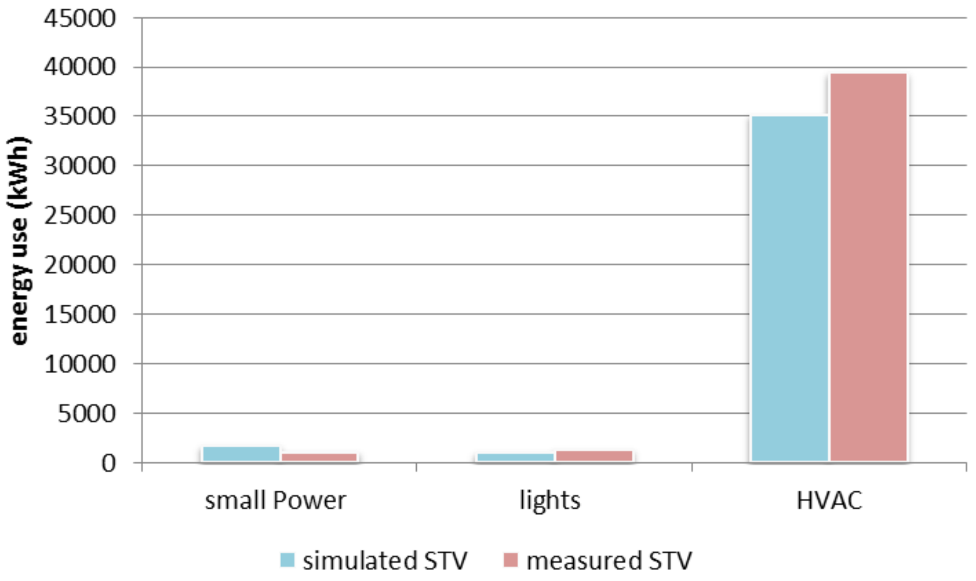


Figure 6-2 STV simulated and measured energy use

To further assess the most significant load in the villas the HVAC energy use monthly consumptions were estimated based on the readings available and the cooling degree days (CDD). The actual HVAC energy use was measured against the CDD for the specific duration, using the resulting regression equation, and from the CDD for each month the monthly HVAC energy use was then predicted. The results suggested reasonable agreement between the predicted and measured HVAC energy consumption, and confirmed, to a certain extent, the actual increase in the STV HVAC consumption and the reduction of the same in the PHV (see Figure 6-3).

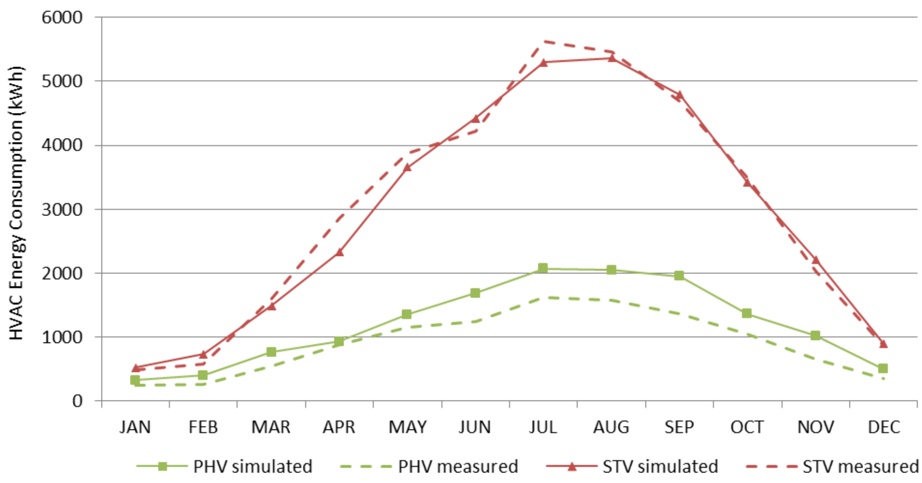


Figure 6-3 PHV and STV measured and predicted HVAC energy use

6.2.2 Indoor temperature

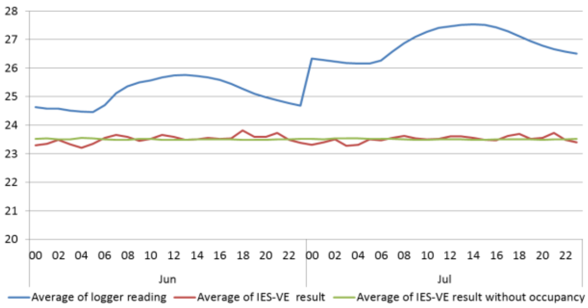
HOBO data loggers were used to measure the indoor air temperature within two logging periods. The first logging data set indicated reasonable proximity between the predicted and the measured air temperature specifically in the bedroom spaces. In the PHV, a maximum difference of 11% was evident in the bedroom spaces. The average difference between the predicted and the measured indoor temperature in BR 1 was 4%, with a maximum difference percentage of 8%. A similar mean difference was found in BR 2; however, the maximum difference reached 10%. The mean M BR space average difference was around 5%, with a maximum variance of 11%.

The living space, on the other hand, showed less agreement. Although the average difference between the two sets of data was only 10%, the maximum differences reached over 20%. This difference was attributed to the misplacement of the loggers, which were most likely effected by stack effect and the solar radiation impact on the ceiling temperature (see Figure 6-4). Additionally, the measured indoor temperatures were also compared against the predicted temperatures, obtained through IES-VE, while the villas were assumed un-occupied (results incorporated Figure 6-4).

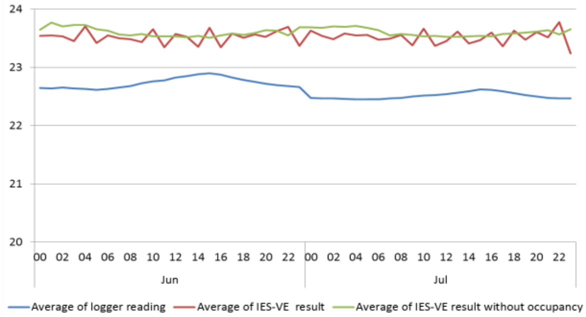
The results of predicted indoor temperatures during un-occupancy had shown close proximity to the predicted indoor temperatures while the villas were assumed occupied, but were observed to be slightly higher. This could be attributed to the ON/OFF cooling system setting used in this project, thus temperatures were likely to be within a specified range. However, it was evident that the fluctuations were eliminated due to the absence of internal gains, and a much flattened temperature variation was obtained in comparison to the hourly temperatures while the villas were assumed occupied.

In the STV, the variances between the predicted and measured data showed variable results (see Figure 6-5). Close proximity was only evident in BR 2, whereas the other inhabitable spaces showed an average difference of 6%, 12% and 26% in BR 1, M BR and LIV respectively. The variance between the measured and predicted indoor temperature in the LIV space was attributed, as in the PHV, to the misplacement of the logger. As noted earlier, a security guard resides in the STV, and it was pointed out during the first logging period that the guard had manipulated the set points of the cooling system in the STV, which may be a possible reason behind the larger variations in the two bedrooms.

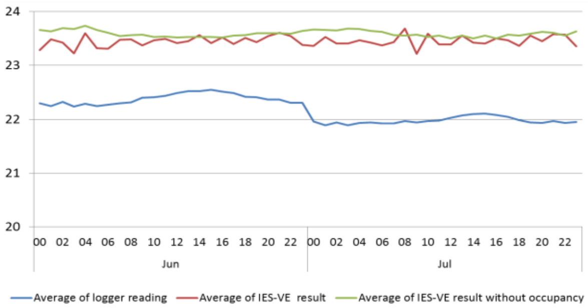
Similar to the PHV indoor temperature analysis, the effect of eliminating internal gains resulting from occupants and household appliances was incorporated in Figure 6-5 . The results indicated a similar outcome to the PHV results. The indoor temperatures predicted during un-occupancy were a flattened image of the temperatures with occupancy in all spaces, except in BR 2 where more fluctuations were evident. This may have resulted due to the lack of an external shade on that part of the building, additionally BR 2 façade was the most exposed to solar heat owing to its orientation.



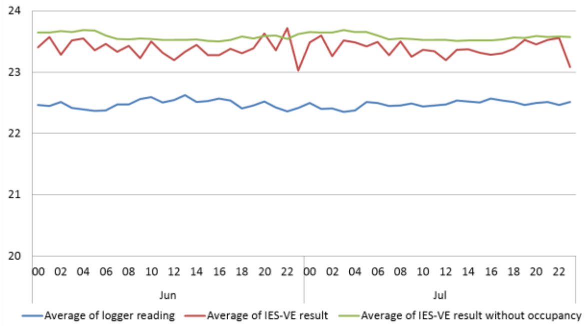
(a) LIV



(b)BR 1

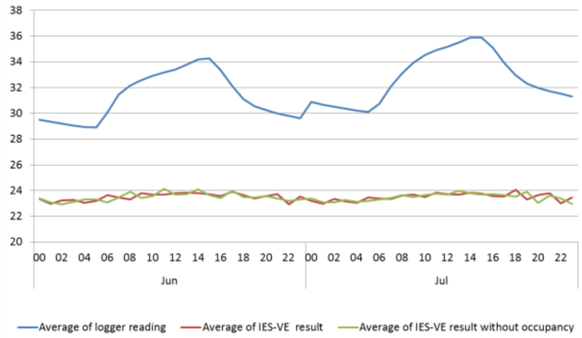


(c) M BR

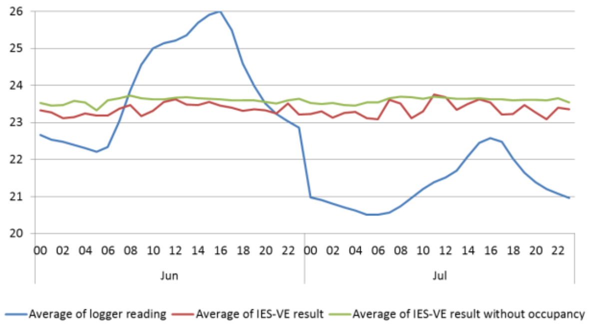


(d) BR 2

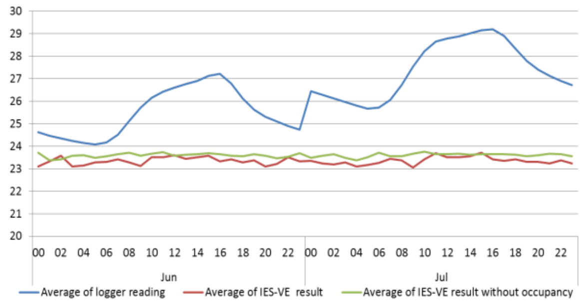
Figure 6-4 Average measured and predicted hourly indoor temperature in PHV



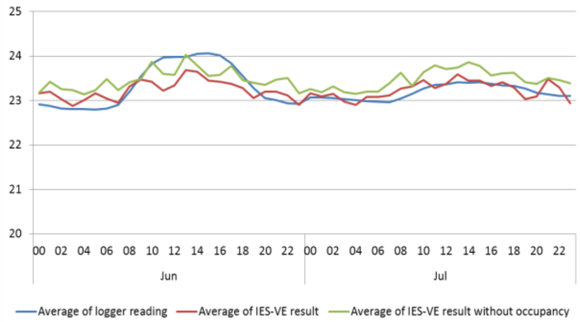
(a) LIV



(b)BR 1



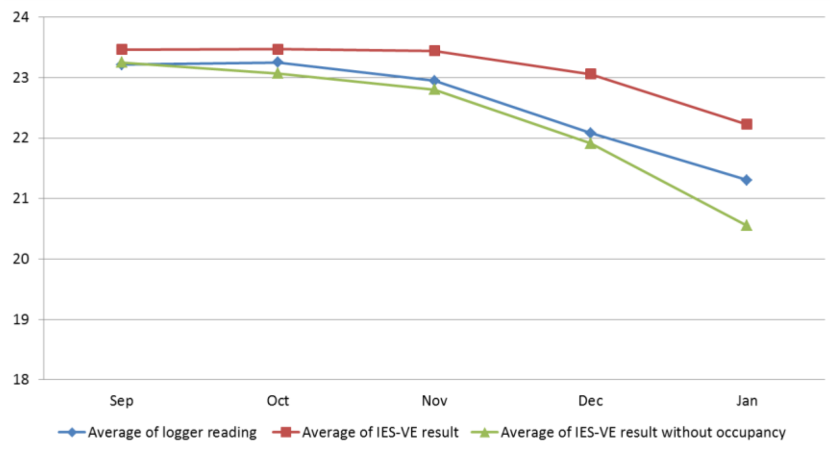
(c) M BR



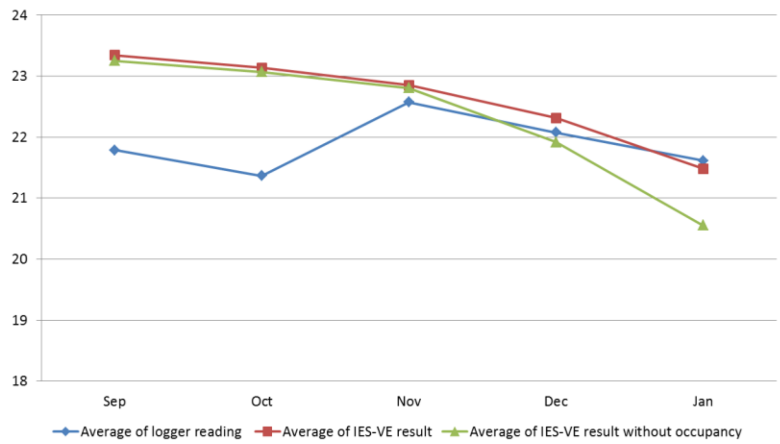
(d) BR 2

Figure 6-5 Average measured and predicted hourly indoor temperature in STV

The second logging was used to better understand the differences encompassed in the living spaces. The results indicated a reasonable proximity between the predicted and the measured data during the first two months, while more divergence was evident during the cooler months in the PHV. The average difference between the predicted and the measured temperature was around 3% in the PHV, and around 9% in the STV (see Figure 6-6). The predicted indoor temperatures while the villas where unoccupied indicated that lower temperatures were to be expected in both villas, possibly due to the absence of internal gains and lower solar gains during the cooler months. It could also be noted that the effect of eliminating the internal gains had a higher impact in the PHV compared to the STV. This agrees with the concept of utilising internal gains in Passivhaus building for heating purposes.



(a) PHV (LIV)



(b) STV (LIV)

Figure 6-6 Average measured and predicted monthly indoor temperature in PHV and STV LIV

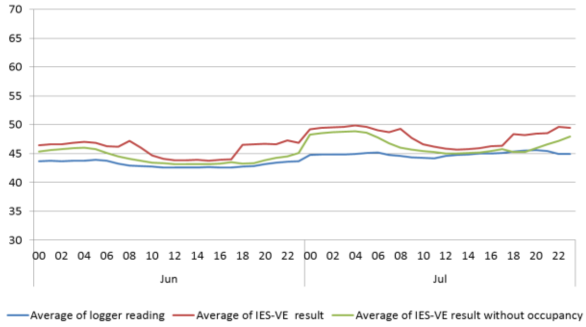
6.2.3 Relative humidity

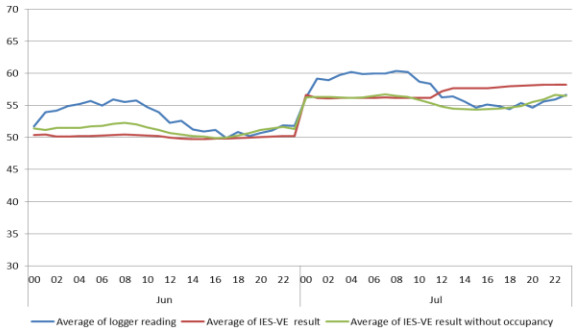
Similar to the indoor temperature, relative humidity levels were measured in all inhabitable spaces. The findings indicated that the average variance between the two sets in the PHV ranged from 0.7% to 7% (see Figure 6-7). While considering relative humidity during non-occupancy a similar outcome of the relative humidity with occupancy could be noticed with a slightly lower prediction in the non-occupancy version. This was valid for both the PHV and the STV.

In the STV, on the other hand, the findings revealed variable results. The average difference between the predicted and the measured relative humidity levels ranged from 11% to 45% during the first monitoring period while assuming the villas occupied (see Figure 6-8).

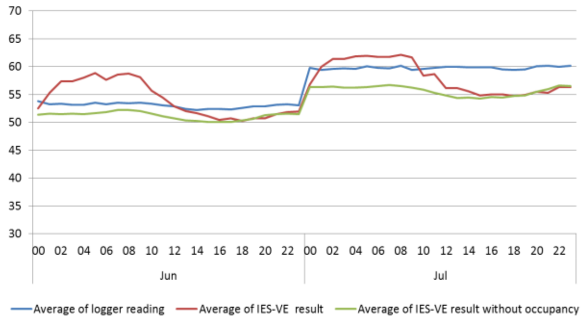
In addition, all logger recordings showed lower relative humidity levels in comparison to the predicted relative humidity levels in the STV. This is most likely as a result of the higher recorded indoor temperature in the STV. Generally, as the moisture content remains at a constant level, any increase in temperature would coincide with a reduced relative humidity level (Szokolay, 2008). In the PHV however, relative humidity levels were measured to a close proximity to the predicted levels.

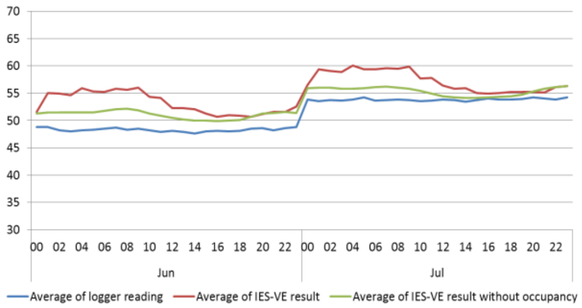
In the second logging period the difference between the predicted and measured PHV LIV monthly average relative humidity levels were found to be around 7%. The percentage of difference had remained within the range of the first logging period, and the actual variance between the two sets was mainly occurring towards the end of the logging period. The average difference of the STV relative humidity levels was still higher, and the average difference was around 26%, with the variance percentage being lower towards the end of the logging period (see Figure 6-9).





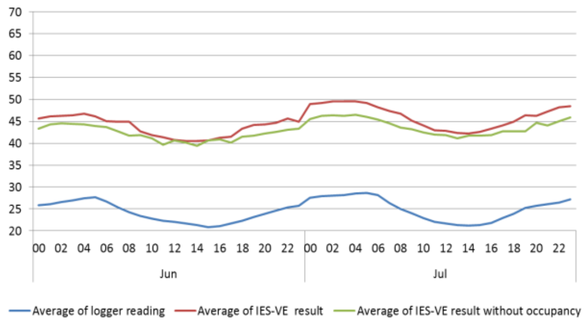
(a) LIV (b)BR 1

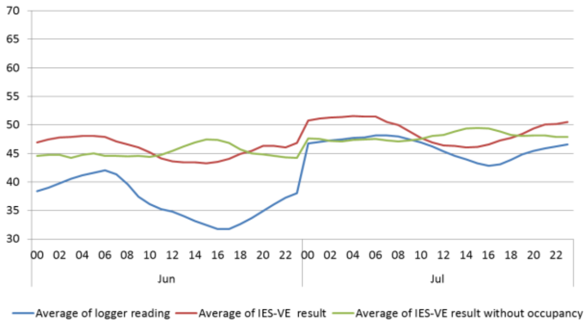




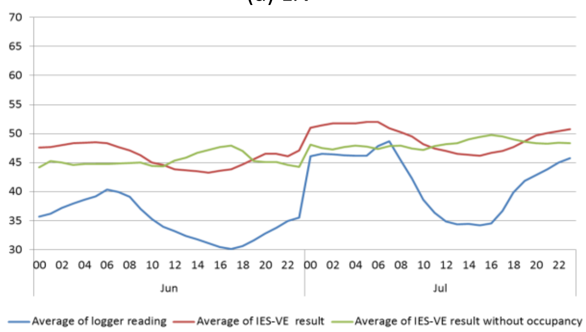
(c) M BR (d) BR 2

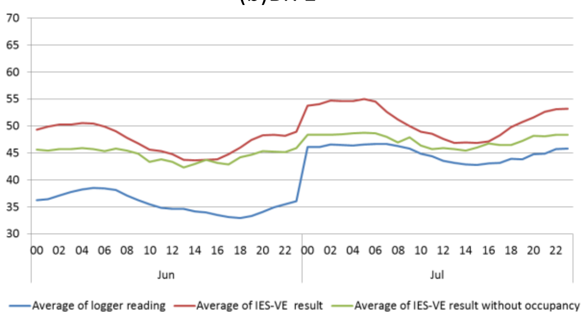
Figure 6-7 Average measured and predicted hourly relative humidity in PHV





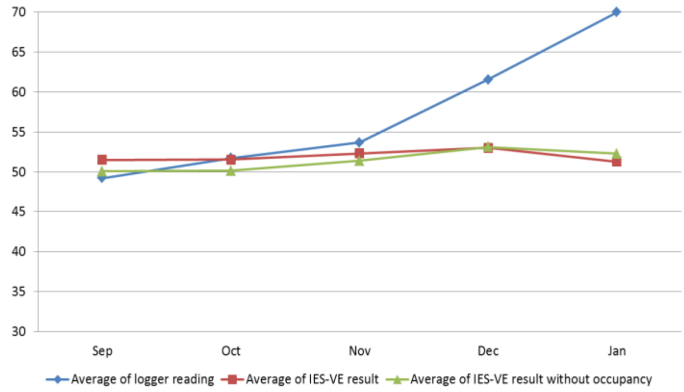
(a) LIV (b)BR 1



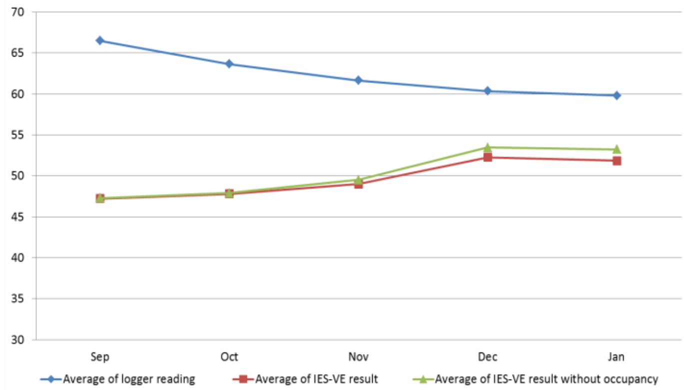


(c) M BR (d) BR 2

Figure 6-8 Average measured and predicted hourly relative humidity in STV



(a) PHV (LIV)



(b) STV (LIV)

Figure 6-9 Average measured and predicted monthly relative humidity levels in PHV and STV LIV

6.3 Current-time Performance Indicators

Three indicators have been used to assess the performance of the Passivhaus project in Qatar. Their selection was based on the perception of the concept of the German Passivhaus standard. A Passivhaus building is characterised by a well-articulated building fabric that ensures high comfort levels for its occupants with minimal energy. Based on the latter concept, three indicators have been selected (energy use, thermal comfort and the thermal envelope) to further evaluate the performance of the Qatar Passivhaus building in comparison to the STV and in accordance to the stringent Passivhaus benchmark. IES-VE and PHPP tools were used to evaluate the performance of the villas. Climate Consultant software was used to better understand Qatar's weather data and the most recommended design strategies. The next sections will highlight the findings classified based on the three indicators.

6.3.1 Energy use

Based on the Passivhaus standard criteria, the total primary energy consumption, which includes household electricity, cooling/heating, and hot water, should not exceed $120kWh/m^2$. Some recent guidelines for the Passivhaus standard have added new classifications that include certifications based on the renewable energy sources invested in a given project. In cooler climates, the heating loads in Passivhaus buildings are extremely low, and most of the energy is likely to be consumed by domestic hot water and appliances rather than by the heating system itself.

However, in hot climates, the cooling load is not directly comparable to the heating load; therefore, the Passivhaus Institute has separately introduced a higher specific cooling demand for hotter climates depending on specific climatic conditions. Ironically, the total primary energy has not been altered to compensate for the increase in the cooling load.

Therefore, constructing a Passivhaus building in a hot climate has further implications, especially when passive cooling does not reduce the cooling load to a significant level. Furthermore, if the building needed humidity control in addition to the ventilation then extra loads would accumulate in the total primary energy. Finally, energy use is also affected by occupant behaviours and the use of household and small power equipment/appliances varies among different age groups and ethnicities.

To overcome the expected increase in energy use, the Passivhaus project in Qatar incorporated the use of photovoltaic solar energy. The entire roof of the PHV was covered with PV panels that generated enough energy to meet the whole load of the PHV.

(a) IES-VE outcomes:

According to simulation, the PHV receives an annual 46,000 kWh of electrical energy generated through its PV panels (see Figure 6-10).

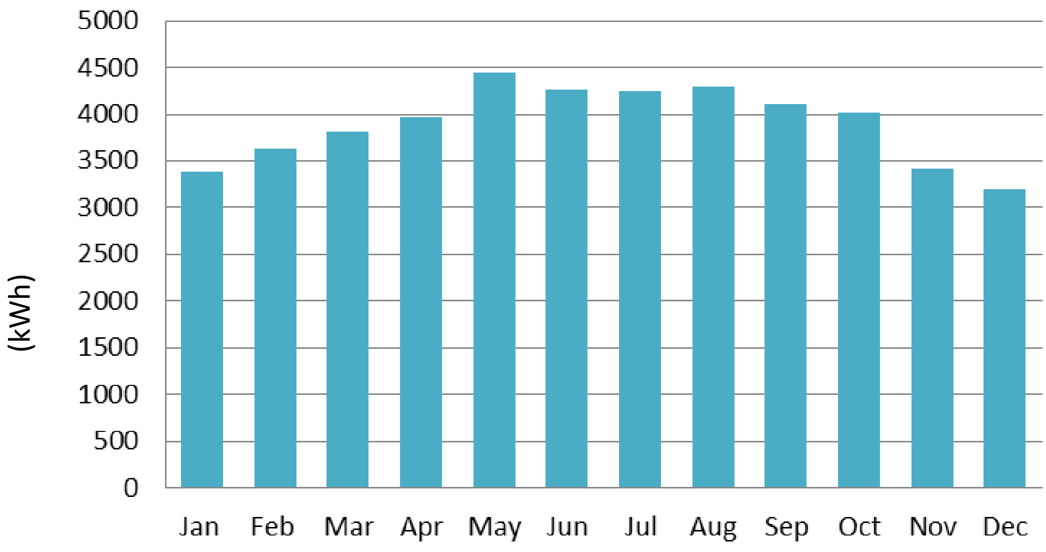


Figure 6-10 Monthly electrical power generated through PV panels in PHV

Based on the building's shell, climate, occupancy and household operational schedules, the PHV was predicted to consume around 21,000 kWh annually. In comparison, the STV was predicted to use 44,500 kWh annually. However since the villas were not occupied at the time of conducting this study , the energy use in the villa was also estimated while eliminating the impact of occupants and other internal gains resulting from the household operational schedules. The predicted energy use was reduced to 16,000 kWh and 38,000 kWh in the PHV and the STV respectively. According to a study conducted three years ago, per-capita electricity consumption in Qatar was estimated at 14,400 kWh annually; the study also referred to Qatar as being one of the highest electricity consumers per capita in the world (Meier, Darwish and Sabeeh, 2013). Building standards may use different definitions to describe and measure the energy demand, such as including embodied energy and considering different floor area measurements, such as using the treated floor, the net and the gross area (CIBSE, 2012).

According to the Passivhaus standard, primary energy accounts for embodied energy, including the energy content in raw materials and energy losses due to distribution, conversion and delivery to the end user. Primary energy is defined as the sum of energy required for heating, cooling, domestic hot water, lighting, auxiliary and household electricity divided by the treated floor area (Lewis, 2014).

Calculation of the treated floor area differs between residential and non-residential buildings according to the Passivhaus standard. For residential buildings the treated floor area includes all living areas, access and circulation and other useful areas such as washroom and storages within the thermal envelope. Spaces within the thermal envelope such as voids, shafts, and areas with heights lower than 1.0 m are not accounted for in the treated floor area (Lewis, 2014; PHPP v. 9, 2015).

The PHV model was designed to be self-sufficient, generating excess energy that could be transferred to the national grid. Additionally, the PHV, without considering the contribution of the PV generated energy, consumes less than half the amount of energy required to operate the STV (see Figure 6-11). The PHV energy use, based on the treated floor area, was predicted to be 135 kWh/m^2; this represents an increase factor of 1.1 compared to the Passivhaus limit. The STV energy use was higher by a factor of 2.5 compared to the PHV, and by 2.8 compared to the Passivhaus standard.

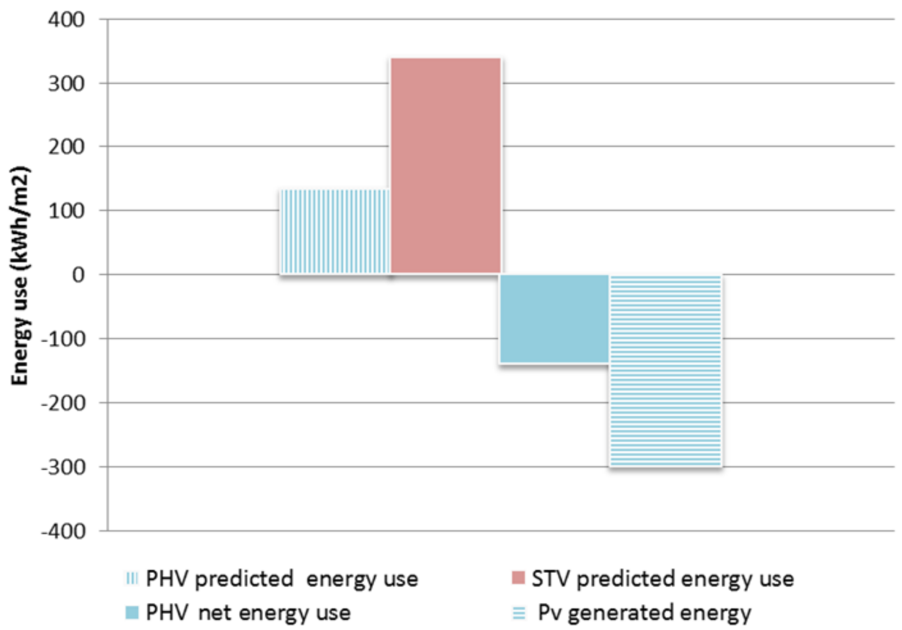


Figure 6-11 PHV and STV annual energy use

(b) PHPP outcomes:

PHPP v.9 was used to acquire the energy balance of the PHV in Qatar. It was mainly used due to the fact that it is the main Passivhaus tool which enables the assessment, certification and the simulation of Passivhaus buildings. It also provides insight into the Passivhaus requirements and recommendations for the specific location based on the climate data selected for each project. The main findings were limited to the space cooling criteria, which included the specific cooling and dehumidification demand and the cooling load.

More skill, input and time were required to fully assess the energy balance of the PHV, based on the time frame given and the amount of technical data available. The basic sheets in PHPP were used as indications towards that performance of the PHV. This comprised the climate, U-values, areas, windows, ventilation, summer vent, cooling units, electricity, and shading and, partly, the solar DHW, PV, and PER worksheets. The PHV outer envelope was replicated as close as possible in PHPP; this included the configuration of the walls, floor and roof and glazing size. However, as a result of the limited technical details related to glazing, window frame and mechanical equipment used in the project, best practices and certified Passivhaus components were assumed. Additionally, the walls and roof were assumed to be treated by special cool colours to reach minimum external solar absorption levels. As a result of the assumptions made, and in conjunction with the PHV geometrical layout and outer fabric configuration, the cooling load criteria were met and, by implanting solar energy and high efficiency lighting, appliances and HVAC systems, the total primary energy was similarly met (see Appendix B).

Based on the preliminary static simulation, PHPP indicated that the cooling demands were within the Passivhaus criteria; the cooling demand was estimated at 57 kWh/m^2.a and the cooling loads at 10W/m^2. The primary energy demand was estimated at 106 kWh/m^2. Although these figures may not reflect the actual PHV performance in Qatar, they indicate that a building built to the PHV layout and building assembly could possibly meet Passivhaus criteria in the hot and arid climate of Qatar.

6.3.2 Thermal comfort

Two thermal comfort models were used to assess thermal comfort in the Passivhaus project, the PMV thermal sensation scale and Schnieders' thermal comfort chart. In addition, an initial analysis was carried out in relation to the weather files using Climate Consultant software. Climate Consultant incorporates the use of the psychrometric chart that analyses general thermal comfort in residential buildings for the specific weather files used.

According to the Passivhaus requirements, overheating should be limited to less than 10% of the hours in a given year in buildings that are passively cooled, or the cooling systems should be adequately sized to maintain an indoor comfort temperature of 25°C during the hot season, when overheating may be anticipated. Additionally, the acceptable moisture content in living spaces is specified not to exceed 12g/kg for more than 20% of the hours in a given year in buildings without active cooling, or not more than 10% of the hours if active cooling is used.

Based on simulation results, the PHV was predicted to sustain indoor temperatures in the bedrooms and living space below 25°C all year round. The moisture content was predicted to be above the 12g/kg benchmark for 3% of the 8760 hours of the year, with higher moisture levels expected in BR 1 and M BR. In the STV, around 14% of the hours were expected to be above 25°C, with 2% of the total hours within the year experiencing air humidity levels above 12g/kg, at higher levels in BR 2 and the LIV space.

(a) Climate Consultant

Based on the psychrometric chart, occupants of any building within Qatar's climate are expected to achieve thermal comfort 8760 hours of the year (i.e. the whole year) by applying certain design tactics to the building envelope and systems. Without the introduction of any design strategy, thermal comfort can be achieved for 20% of the time in a given year. Climate Consultant presents an estimated comfort percentage time against each applied design strategy, adding towards the overall achieved occupant thermal comfort. The most dominant strategy was represented by applying mechanical cooling to the buildings. Additionally, other strategies were highlighted that would effectively reduce the cooling loads of buildings, such as dehumidification, shading, and the reduction of internal heat gains. Through Climate Consultant's initial assessment it was evident that the PHV, the STV – or in fact any other building within Qatar's climate – would need mechanical cooling for at least 60% of the time annually; by adopting other strategies the dependence on the cooling systems could be lowered by another 10% at the most (see Figure 6-12).

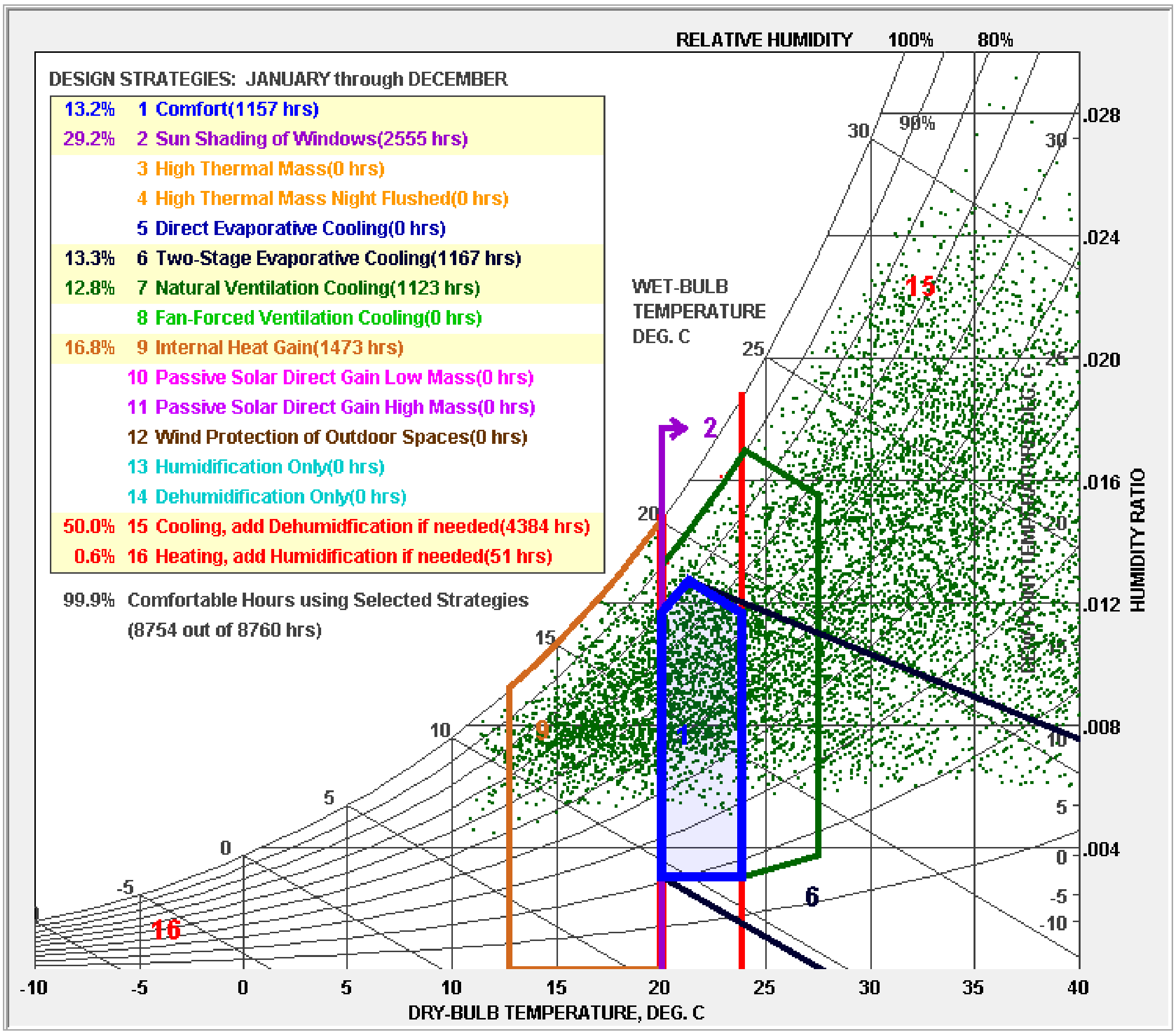
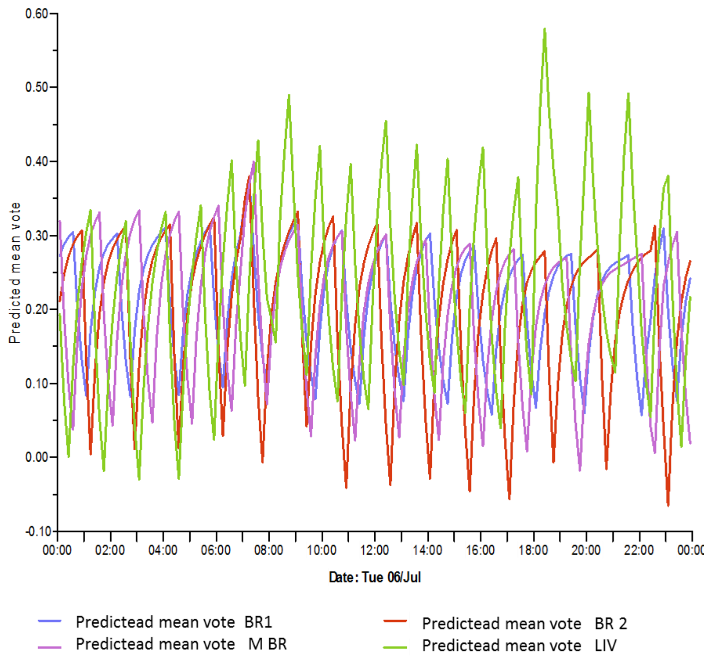


Figure 6-12 Climate Consultant psychrometric chart for Doha, Qatar

(b) PMV thermal sensation scale

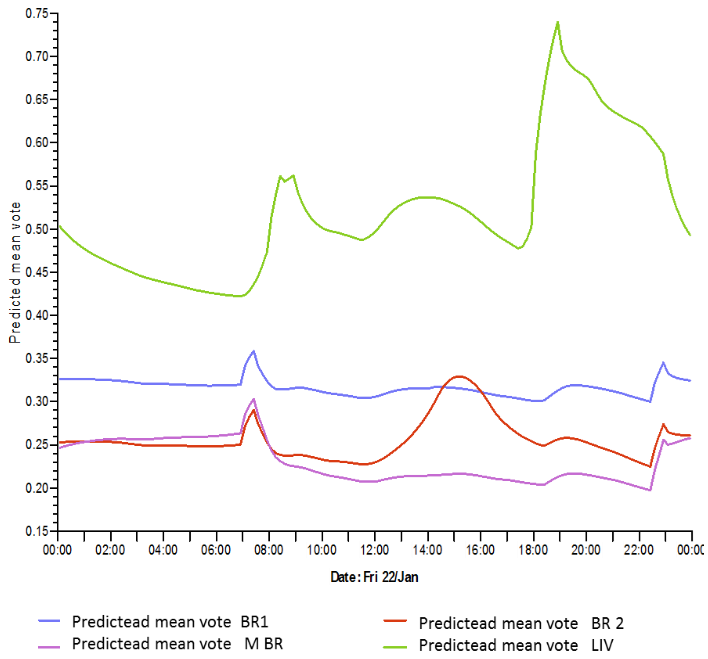
The PMV model was used to assess the thermal comfort of the PHV and the STV. The findings indicated that both villas had achieved a satisfactory level of thermal comfort. Most of the votes were within the neutral band (0) between (+1, -1) on the thermal sensation scale. The PHV, however, indicated a better consistency in terms of maintaining the votes mostly within the band (+0.5,-0. 5) throughout the hottest and coolest days for the bedroom spaces, and marginally above that level in the LIV space during the hottest day. During the coolest day a different scenario was predicted: although the bedroom spaces' occupants were expected to vote between (+0.5,-0.5), occupants in the LIV space were expected to vote above +0.5, specifically during the end of the day, when most occupants are expected to use the space.

In the STV, the PMV thermal sensation scale indicated that during the hottest day occupants are likely to be voting closer to the slightly warmer sensation, although not completely exceeding it; this was similarly evident for the LIV space. The votes for all spaces during the coolest day exceeded the +0.5 band, with the maximum vote expected in BR 2 (see Figure 6-13 and Figure 6-14).



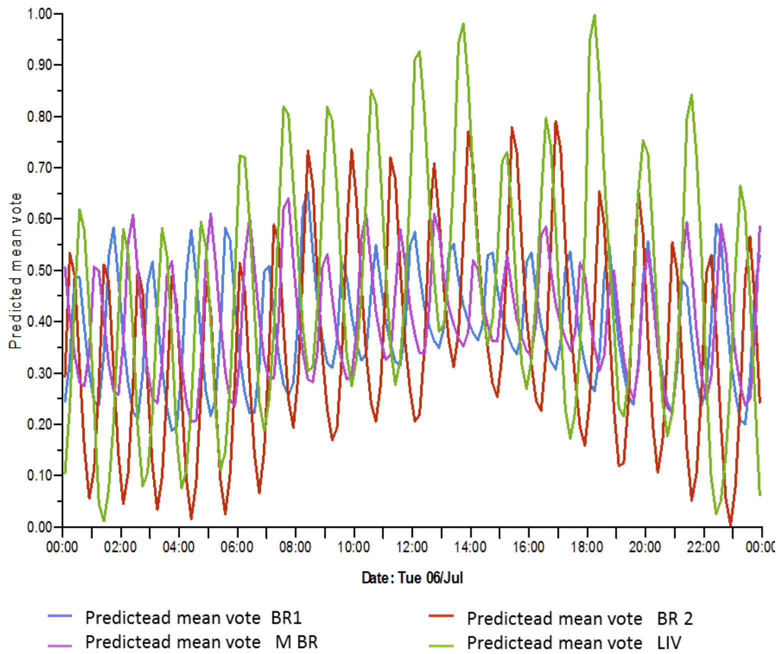
(a) PMV during the hottest day

Figure 6-13 PHV PMV



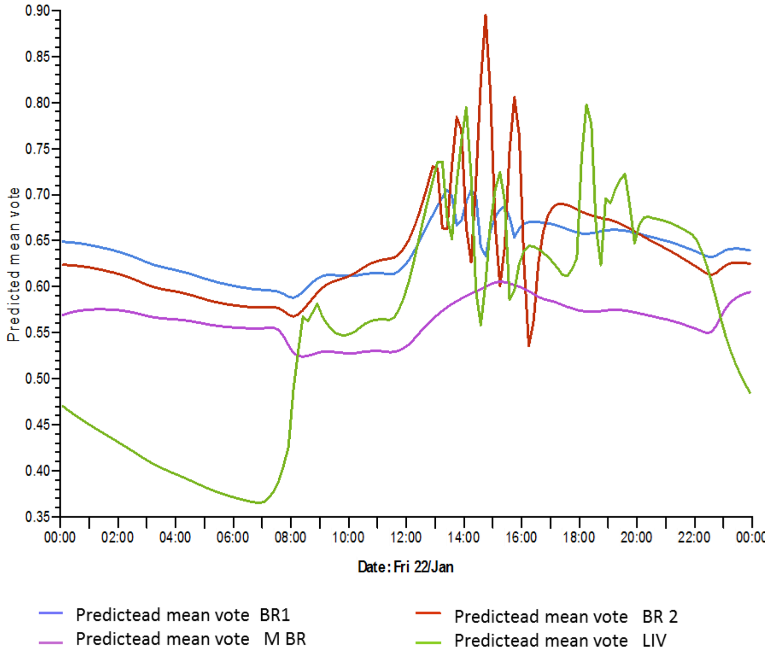
(b) PMV during the coolest day

Figure 6-13 PHV PMV



(a) PMV during the hottest day

Figure 6-14 STV PMV



(b) PMV during the coolest day

Figure 6-14 STV PMV

(c) Schnieders' thermal comfort chart

A similar thermal comfort pattern was predicted by using Schnieders' thermal comfort chart. The two villas indicated a satisfactory level of thermal comfort, although the comfort level of the PHV was repeatedly more consistent. The hourly operative temperature and relative humidity levels of the PHV were mostly sustained within the inner thermal comfort zone; the operative temperatures were confined beyond the 25°C limit, whereas the associated relative humidity levels extended between the 30%-70% relative humidity levels, with 355 hours above 70% and 163 hours below 30%. The STV thermal comfort chart showed a wider range of operative temperature and relative humidity levels. Several hours during the year were predicted to be within the extended thermal comfort zone or beyond, showcasing operative temperatures that ranged from 19°C to 26°C, with 240 hours predicted to be below 19°C and 318 hours above 26°C. The relative humidity levels ranged from 30% to 70%, with 941.0 hours above 70% and 224 hours below 30% (see Figure 6-15 and Figure 6-16).

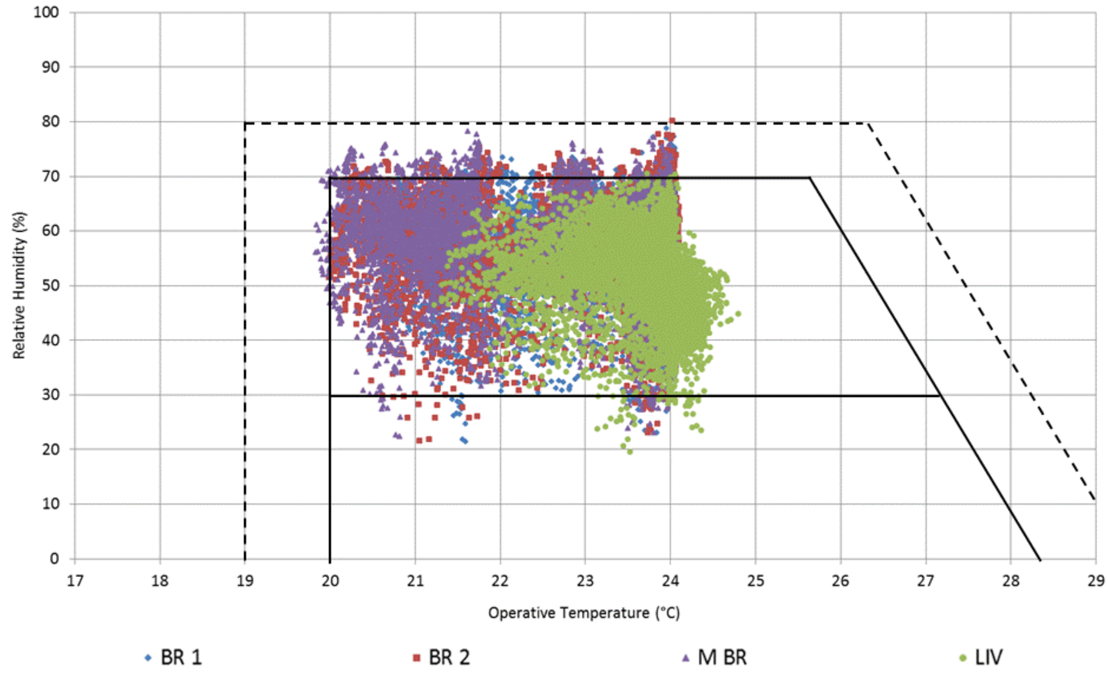


Figure 6-15 PHV Schnieders' comfort chart

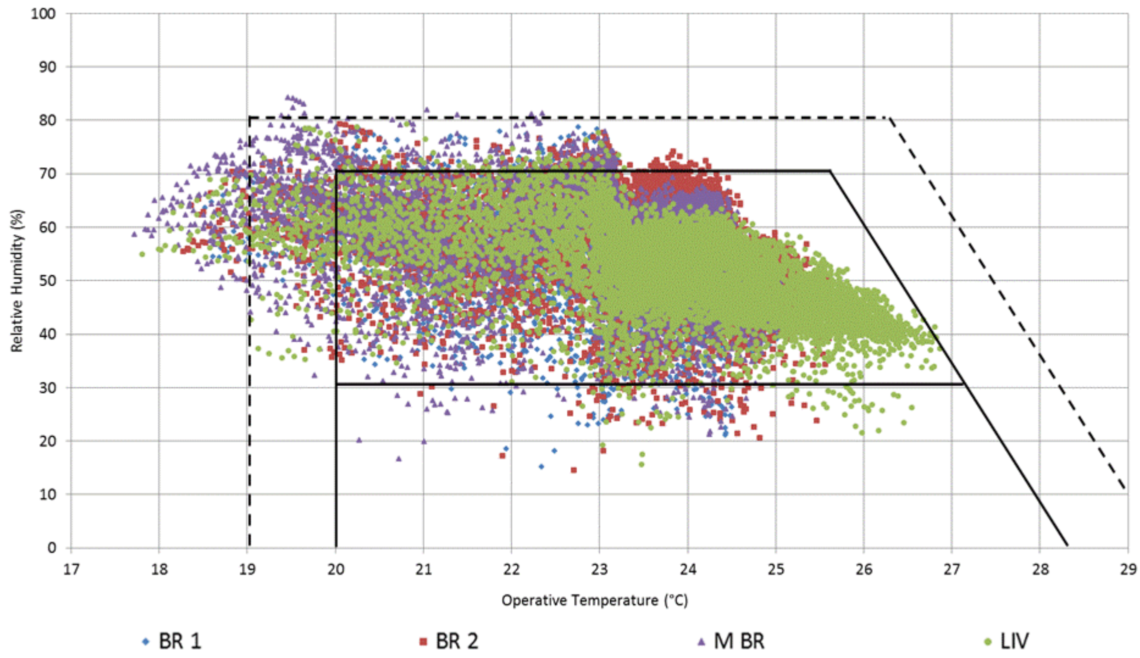


Figure 6-16 STV Schnieders' comfort chart

6.3.3 Thermal envelope performance

The effectiveness of the PHV's highly articulated building envelope was measured by disabling the cooling option in IES-VE. The sustained average monthly operative indoor temperatures were measured in comparison to the mean outdoor bulb temperature. The outcomes were compared to the STV indoor operative temperatures by using a similar approach. The findings indicated that the robust envelope of the PHV was able to maintain the indoor operative temperatures well below the mean outdoor bulb temperature, more specifically, during the hot months in all living spaces. In comparison, the average monthly operative temperatures of the STV were just above the mean outdoor dry bulb temperatures for almost all seasons (see Figure 6 17).

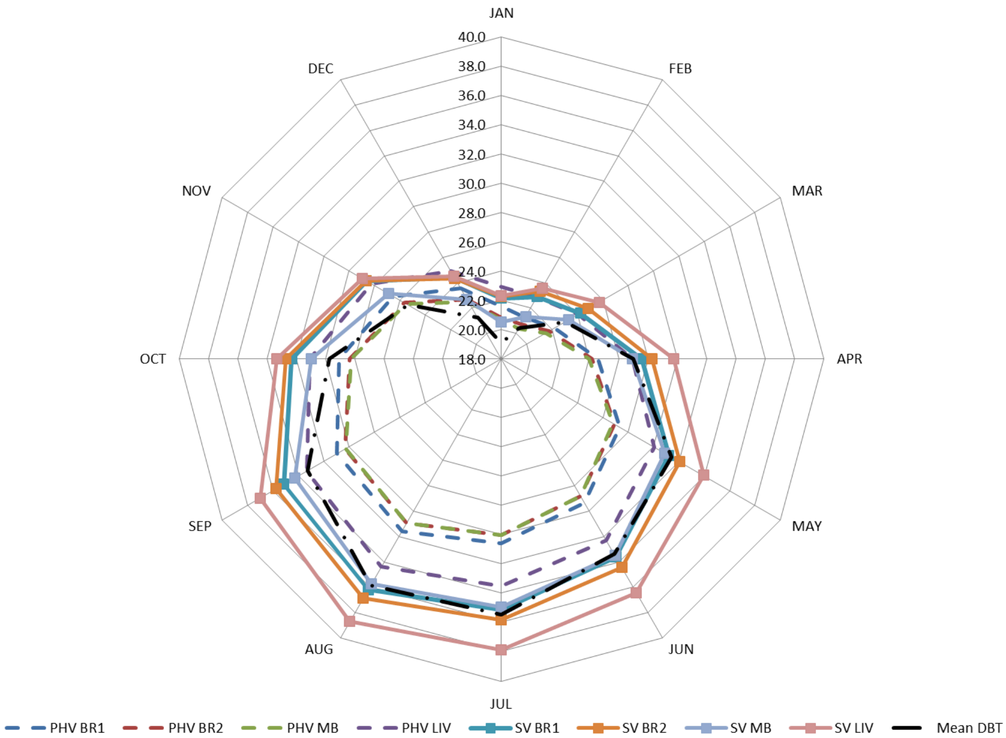


Figure 6-17 PHV and STV thermal envelope performance

6.4 Future Performance Implications

Three future climate scenarios were investigated, considering a medium to high climate impact on the Passivhaus project in Qatar. Timeline series for 2020, 2050 and 2080 were chosen using morphed (EPW) weather files generated through the Climate Change World Weather Generation tool developed by the University of Southampton's Sustainable Energy Research Group. The selection of the weather files was based on a comparison between (EPW) file sets generated through two statistical generation weather tools, Meteonorm and the Climate Change World Weather Generation tool. The Climate Change World Weather Generation tool provided a higher impact (refer to section 4.3.1) and was chosen as the worst-case scenario among the two sets examined. The three performance indicators examined in the previous section are used in this section to assess the performance of the PHV under climate change impacts. All the building components, construction materials and PV panel efficiency were assumed to be identical for the three timeline scenarios. PV degradation rates, due to dust and aging and solar reflectance index degradation for white surfaces, were overlooked, and the current systems and construction materials were assumed identical for the three timelines. In general, all building systems, such as in the PHV in Qatar, may be upgraded for better performance in the future, and solar systems and technologies are also expected to advance, and buildings are expected to need further maintenance throughout their lifespan. If the PHV project remains an asset of the QGBC, further development and maintenance are likely to take place. Since the main objective of this study was to assess the performance of a Passivhaus model in a hot and arid climate, and not the implementation of other advanced technologies, such factors were considered less important for the future climate analysis.

6.4.1 Energy use

Based on simulation, the PHV and the STV energy use was expected to increase by an almost constant increase factor of 1.1 in the different timeline series. The PV generated energy was still predicted to cover the whole load of the building, with a surplus load that decreased through the three timelines, as a result of the increased actual energy use. The increase in energy was mainly attributed to the increase in the cooling demands (see Figure 6-18).

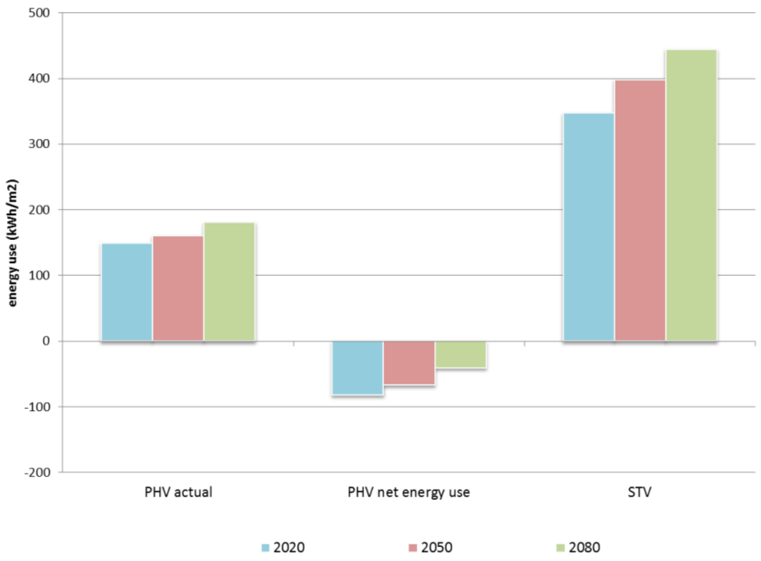


Figure 6-18 PHV and STV energy use 2020, 2050, 2080

The space cooling demands for the PHV, according to the Passivhaus criteria for Qatar's climate, should be less than or equal 27 kWh/m^2.a, this is based on the calculations obtained through the PHPP and is denoted as the standard criteria or, alternatively whenever necessary an upper limit is allowed by the standard which in this case is less than or equal to 60 kWh/m^2.a, or the peak cooling load should be less than or equal to 10 W/m^2 (please refer to Appendix B for the PHPP verification sheet). These benchmarks, as stated, were obtained through PHPP calculations based on the climate data provided, moisture loads and necessary air change rates and internal heat loads. According to IES-VE, the highest total cooling reached 34.9 kWh/m^2.a in the 2080 scenario, compared to 23 kWh/m^2.a in the present day scenario. In comparison, the electrical total cooling in the STV reached 190 kWh/m^2.a in 2080 compared to 96.5 kWh/m^2.a in the present time. In the STV, the total cooling demand increased from 14.7 MWh in the present time to 17.9 MWh in 2020 and to 25.4 MWh in 2080, and in the PHV from 3.5 MWh in the present scenario to 3.9 MWh in 2020 to 5.4 in the 2080 scenario (sees Table 6-2).

Table 6-2 PHV and STV cooling demands

Cooling demands (kWh/m^2.a)	2020	2050	2080
PHV	24.9	28.8	34.9
STV	114.7	156.1	190.6

6.4.2 *Thermal comfort*

The Passivhaus standard thermal comfort criteria were partly maintained in the PHV for the three timelines. The indoor temperatures in all the spaces in the PHV were below 25°C. The moisture content, however, was higher than the Passivhaus standard at 11%, 12.7% and 24.5% for the years 2020, 2050 and 2080 respectively, compared to 3% in the current time. The 2020 scenario in the STV had indicated that the indoor temperatures were expected to be above 25°C for 12.3% hours of the year with a moisture content that exceeded 0.12g/kg for 1% of the hours. The 2050 scenario, on the other hand, indicated that the indoor temperatures were above the benchmark for 12.9% of the hours, while the moisture content was higher than the benchmark for 4.6% of the hours. The 2080 scenario showed an increase in moisture content above the acceptable benchmark for 13.1% of the time, while the air temperatures were above 25°C for only 4.7% of the hours. In the present day scenario around 14% of the hours were expected to be above 25°C, with 2% of the total hours experiencing air humidity levels above 12g/kg.

(a) Climate Consultant

Climate Consultant for the three timelines indicated that the thermal comfort of the occupants would be attained dominantly through mechanical cooling, in addition to other design strategies that were expected to reduce the cooling loads for residential buildings in Qatar. The moisture content was expected to increase through the different timelines; the percentage of the dehumidification strategy had increased from 0% in the current time to 6.7% in the 2020 scenario and to 8.9% in the 2080 scenario (see Figure 6-19) – please refer to Appendix C for the psychrometric chart for 2020 and the 2050 weather file.

The conventional cooling approach had also risen, from 50 % in the present day to 55% in the 2020 timeline and to 63% in the 2080 scenario. Unlike the present day, 2020 and 2050 timelines, occupant thermal comfort was expected to be fully met at 100% by applying the different design strategies embedded in Climate Consultant; however, the 2080 timeline predicted that for a slight 1% (99) of the hours during the year occupants were expected to experience discomfort regardless of the mechanical cooling and other parametric design approaches.

The findings therefore suggested that more reliance will be placed on mechanical means to achieve thermal comfort through cooling and dehumidification 60 years from now. Additionally, much attention should be given to building envelopes to reduce the amount of heat transfer through the skin of buildings in the area in order to reduce the cooling demand.

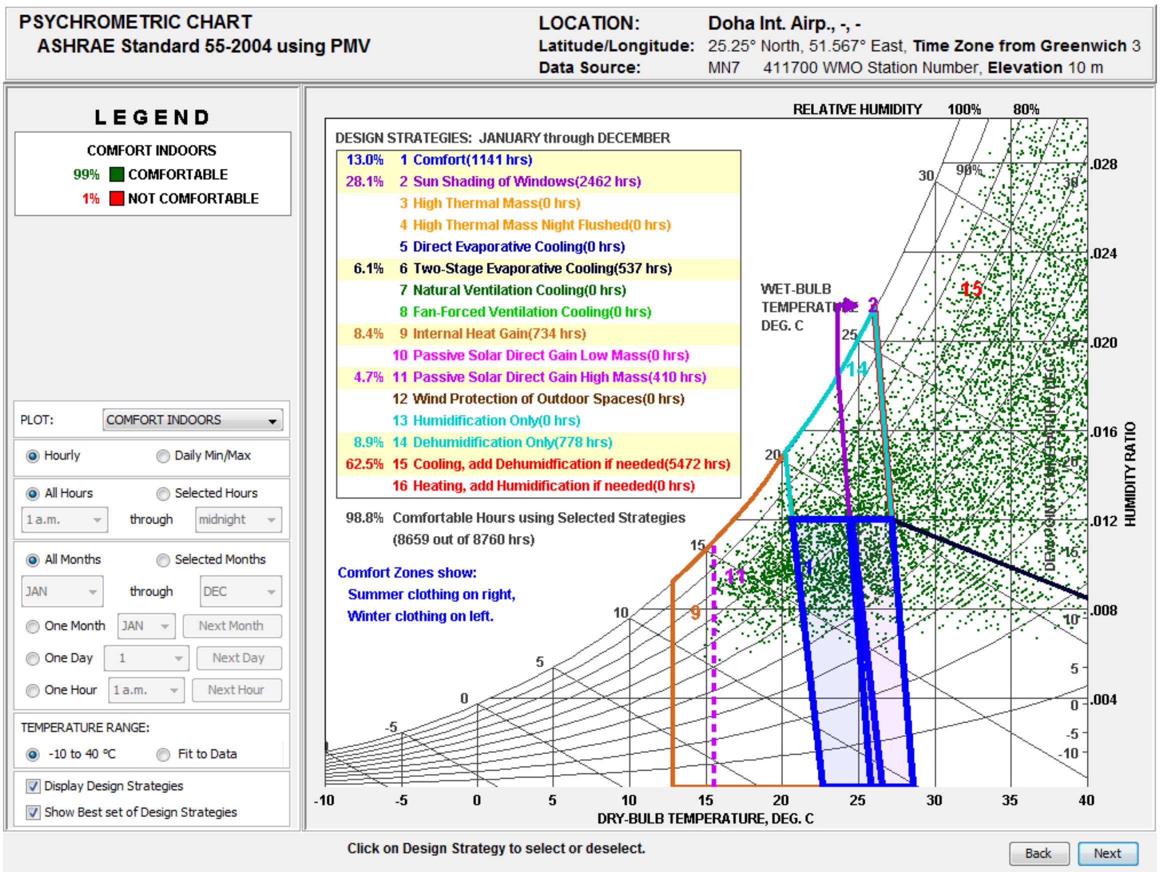
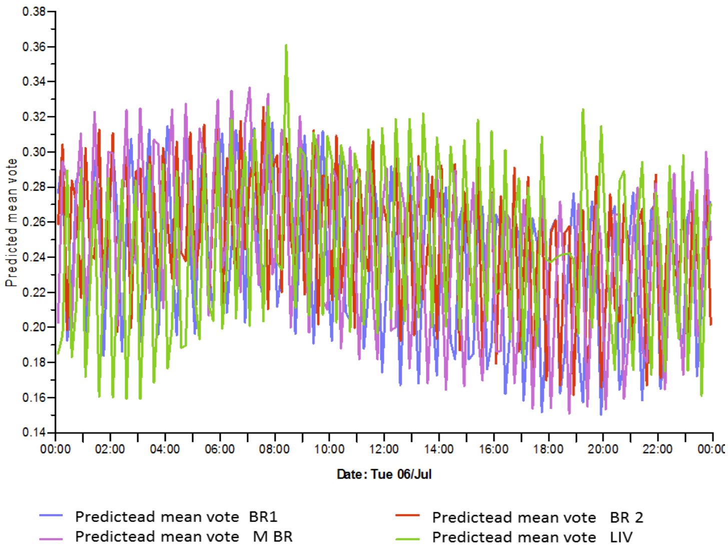


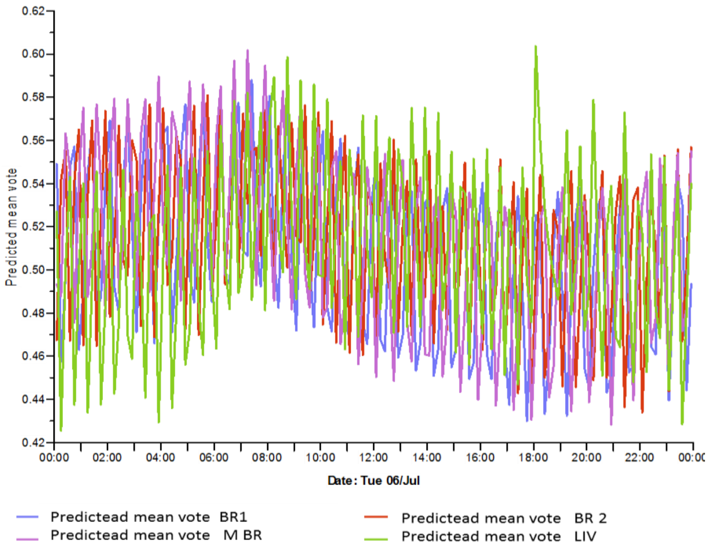
Figure 6-19 Climate Consultant psychrometric chart for 2080 weather file

(b) PMV thermal sensation scale

The PMV of the PHV occupants was expected to be within the neutral score for the three timelines. In the STV, the occupants were similarly expected to experience acceptable levels of thermal comfort, although a slightly warmer sensation was predicted for 2%, 2.8% and 8% of the time in the 2020, 2050 and 2080 scenarios respectively during the hotter months, in comparison the STV in the present day scenario had indicated that all votes were below +1.0 (see Figure 6-20 and Figure 6-21).

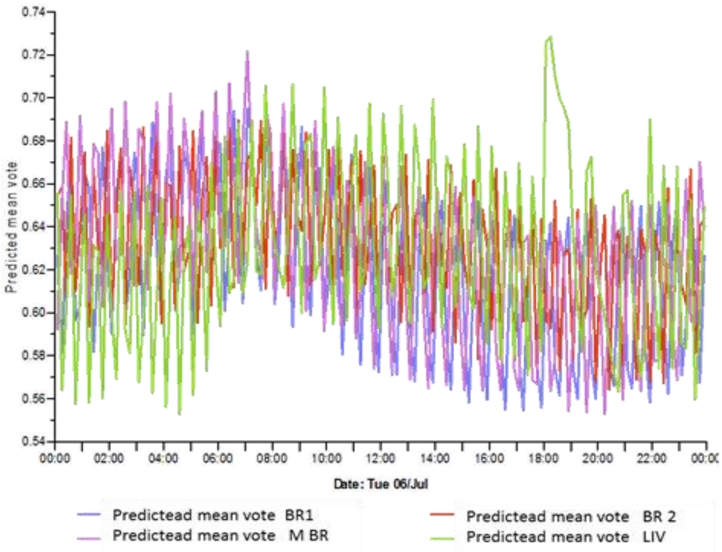


(a) 2020



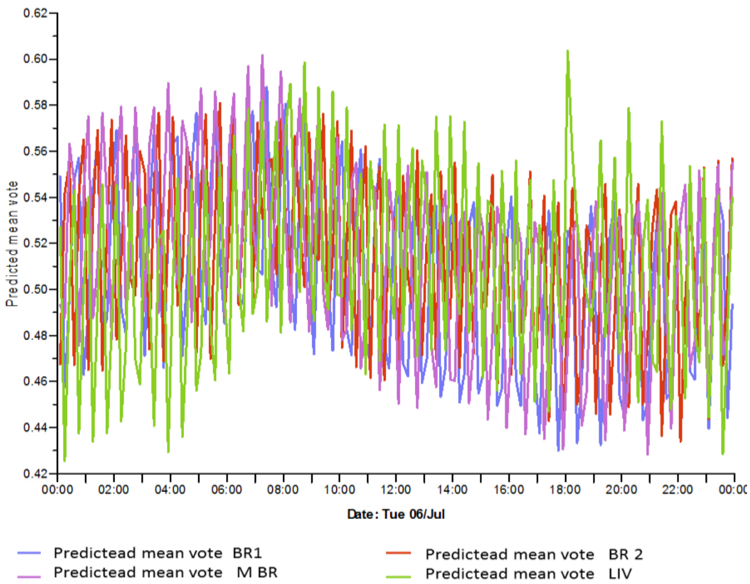
(b) 2050

Figure 6 - 20 PMV for the PHV during the hottest day



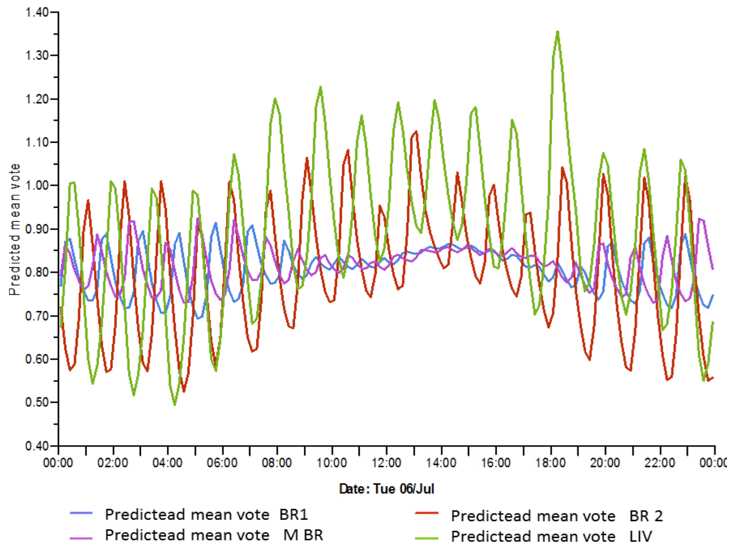
(c) 2080

Figure 6-20 PMV for the PHV during the hottest day

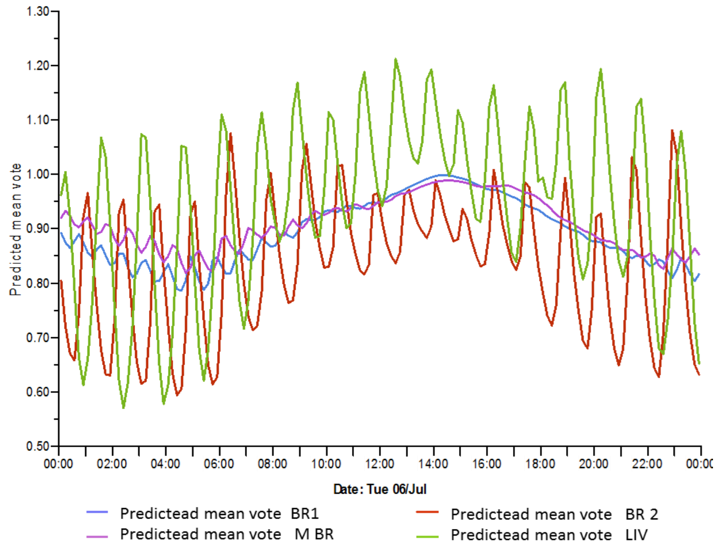


(a) 2020

Figure 6- 21 PMV for the STV during the hottest day



(b) 2050

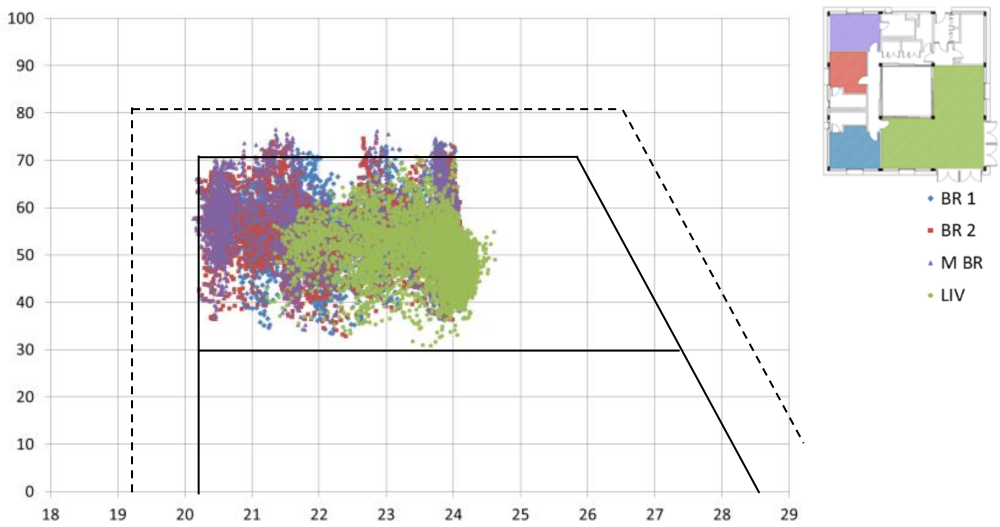


(c) 2080

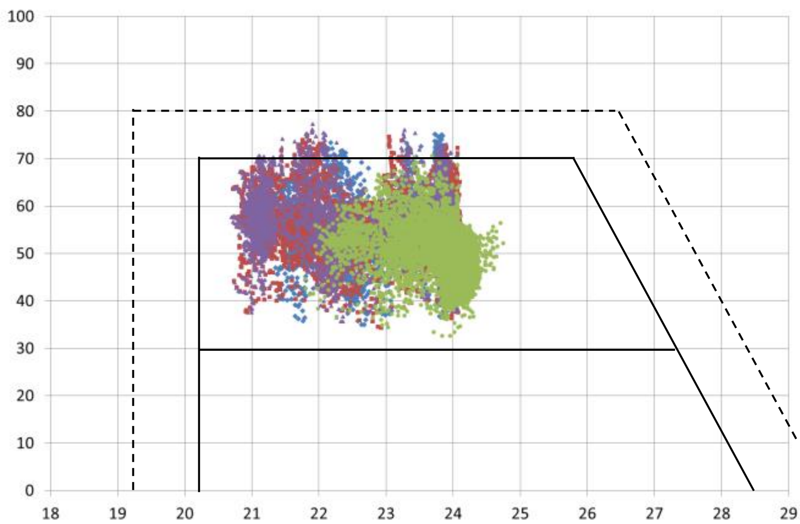
Figure 6-21 PMV for the STV during the hottest day

(c) Schnieders' thermal comfort chart

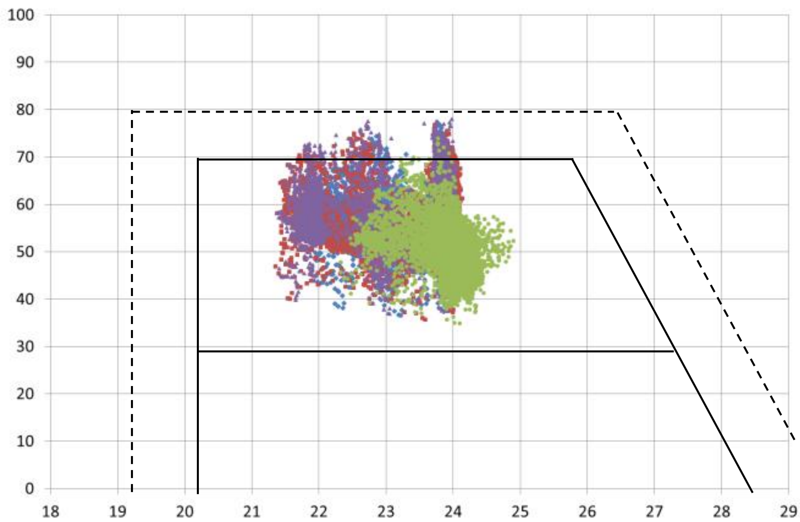
Based on Schnieders' thermal comfort chart, the PHV had maintained thermal comfort mainly within the inner thermal comfort zone for all the scenarios. The STV, on the other hand, indicated that a number of hours were either within the extended thermal comfort zone or even beyond. In the STV thermal comfort chart a clear shift towards the warmer side was evident, whereas in the PHV a stronger unsubstantial boundary confined the operative temperatures and relative humidity levels to be sustained within the inner thermal comfort zone (see Figure 6-22 and Figure 6-23).



(a) 2020

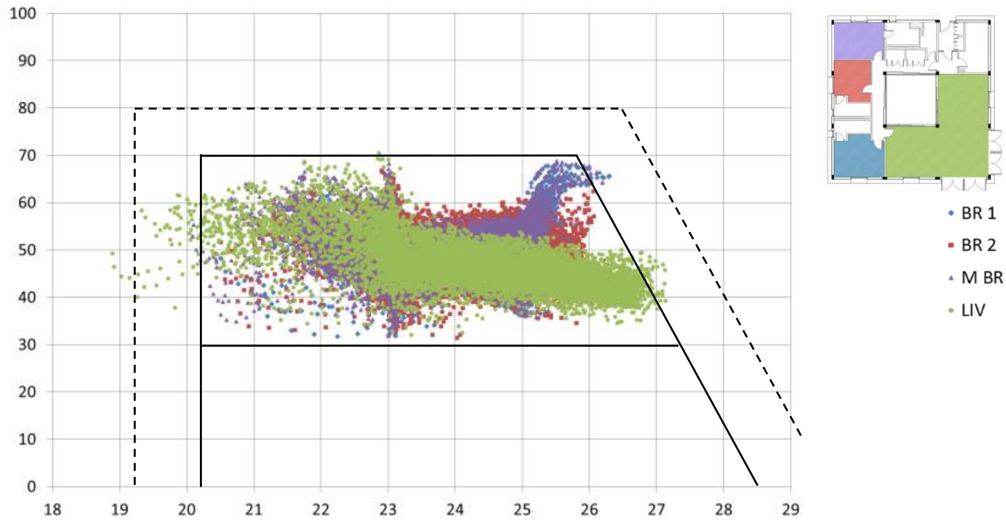


(b) 2050

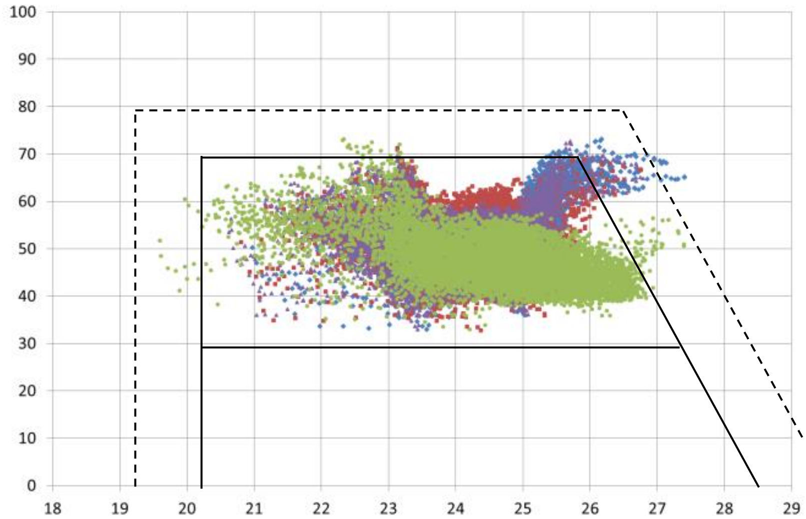


(c) 2080

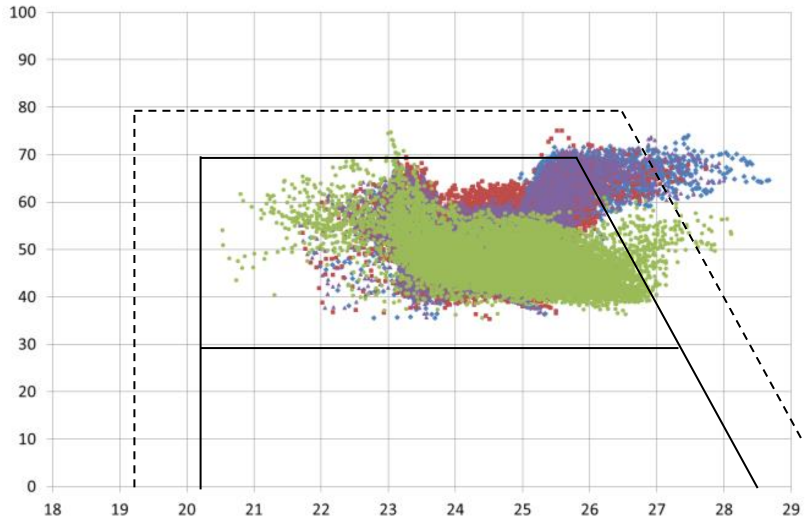
Figure 6-22 PHV: Schnieders' thermal comfort charts for the PHV



(a) 2020



(b) 2050

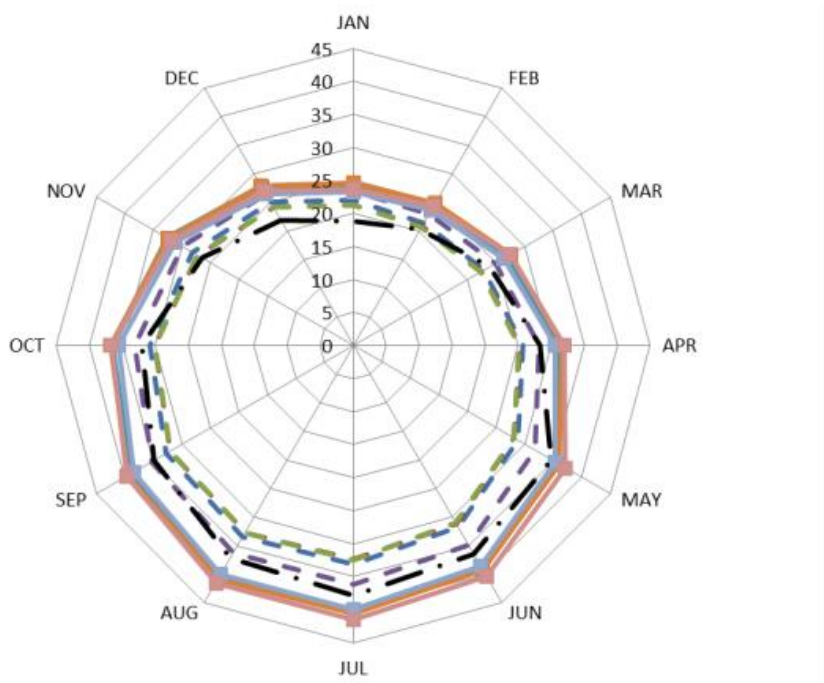


(c) 2080

Figure 6-23 STV: Schnieders' thermal comfort charts for the STV

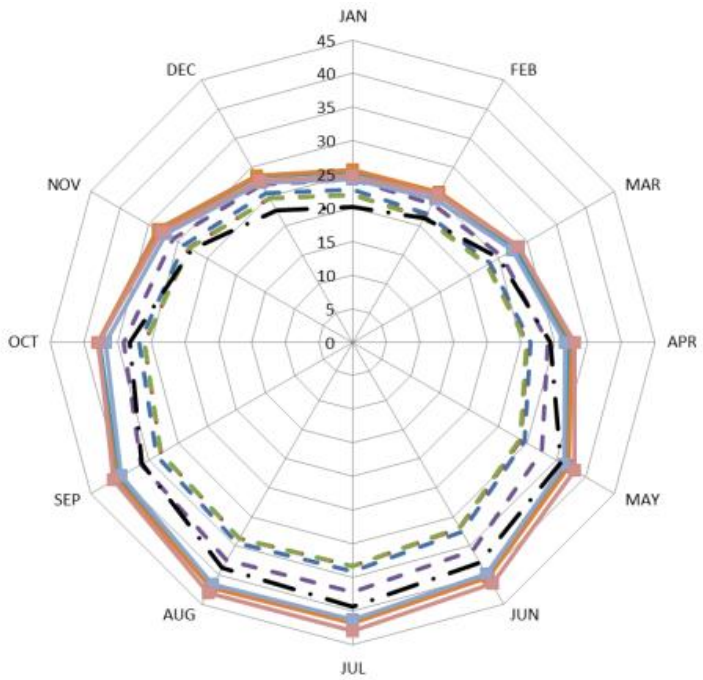
6.4.3 Thermal envelope performance

The thermal envelope performance was assessed for the three timeline series by measuring the effectiveness of the outer skin to withstand the extreme outdoor heat. The assessment was carried out by conducting a comparison between the average monthly operative temperature and the outdoor dry bulb temperature while disabling the cooling option in IES-VE. The findings indicated that the PHV extensive shell was able to effectively retain the indoor temperature below the outdoor temperature, specifically during the hotter months, in the living spaces in all three timelines. The STV thermal envelope, on the other hand, was not robust enough to keep the heat from entering into the living spaces. The outcomes indicated that the indoor temperatures were above the outdoor dry bulb temperature during the hot and cold seasons. Additionally, the gap between the indoor temperature and the outdoor dry bulb temperature was widening through the three timeline series. In the 2020 series, the STV indoor temperatures were slightly above the extreme outdoors; in the following series, however, the distance between the two variables was gradually increasing. Figure 6-24 shows the results graphically.

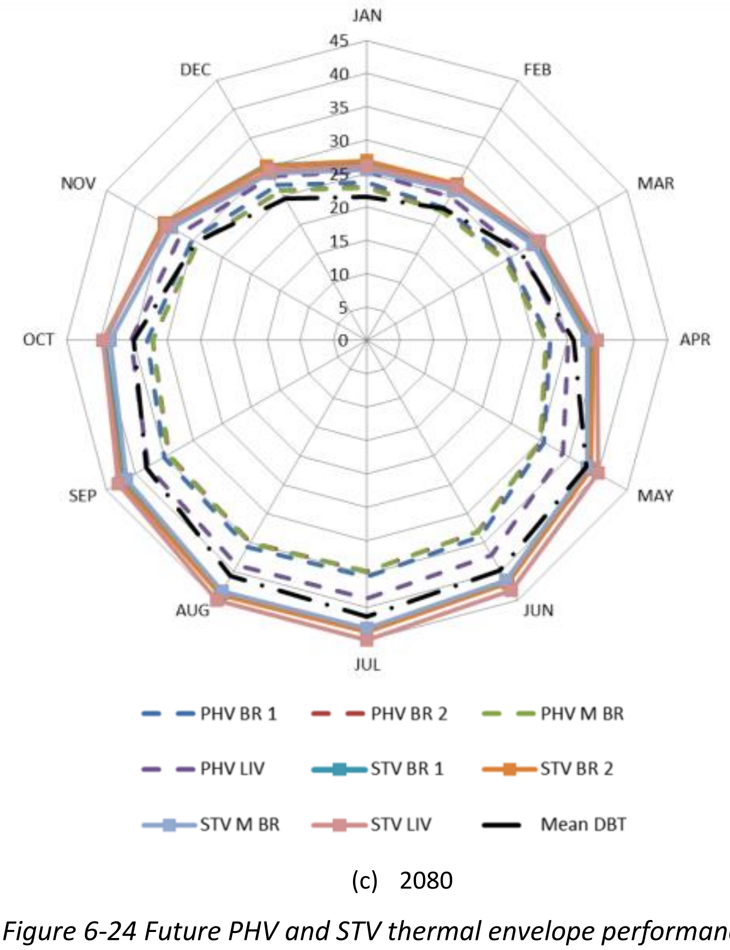


(a) 2020

Figure 6-24 Future PHV and STV thermal envelope performance



(b) 2050



(c) 2080

Figure 6-24 Future PHV and STV thermal envelope performance

6.5 Parametric Study

Based on the findings presented in the previous sections, the performance of the PHV has been proved to be successful in comparison to with the STV in terms of energy use and the thermal envelope performance. One of the overarching aims of this research was to obtain an energy-efficient model that could be compatible for the climate of the GCC. The performance of the STV was found to be better than the performance of a business-as-usual villa in Qatar in terms of energy use.

As noted in earlier chapters, the STV was constructed to achieve one star according to the GSAS performance-based system; therefore, the energy consumption in the STV was 20% less than a more typical (a business-as-usual) building. The focus of this investigation was to evaluate how close the STV would be in terms of energy use and cooling demands if a number of its parameters were altered to match the PHV's special features.

Based on the literature review and inspired by the concept of the Passivhaus standard, the building thermal envelope was the chosen parameter for the parametric study. A number of researchers have conducted similar parametric studies to measure the extent of parametric changes on the performance of buildings by exploring the impact of the variations within the built environment on a number of areas, such as energy use, thermal comfort, peak loads and economical payback (Alaidroos and Krarti, 2015; Croitoru et al., 2016; Fallahtafti and Mahdavinejad, 2015).

In a recent review, the building envelope, glazed surfaces and shading systems were found to be the parameters that had repeatedly been used in parametric energy-efficient studies. In addition, according to the study, heating/cooling systems have recently been considered by researchers (De Boeck et al., 2015). In this study, the STV was upgraded by focusing on the building envelope and the glazed surfaces. The insulation thickness in the STV was increased to match the PHV's thermal transmittance level; similarly, the glazed surface insulation was altered to closely match the PHV. In addition, other factors were altered, such as the window-to-wall ratios (WWR) and shading systems, to measure the extended impacts of further enhancements on the thermal envelope.

6.5.1 Study approach

As described earlier, the STV was constructed according to the GSAS rating system, which is mainly applied to public buildings in Qatar at present rather than private buildings. The wall was insulated by introducing a 50mm air gap between the two concrete blocks leafs. The roof was insulated by a 50mm extruded polystyrene insulation layer (see Figure 6-25).

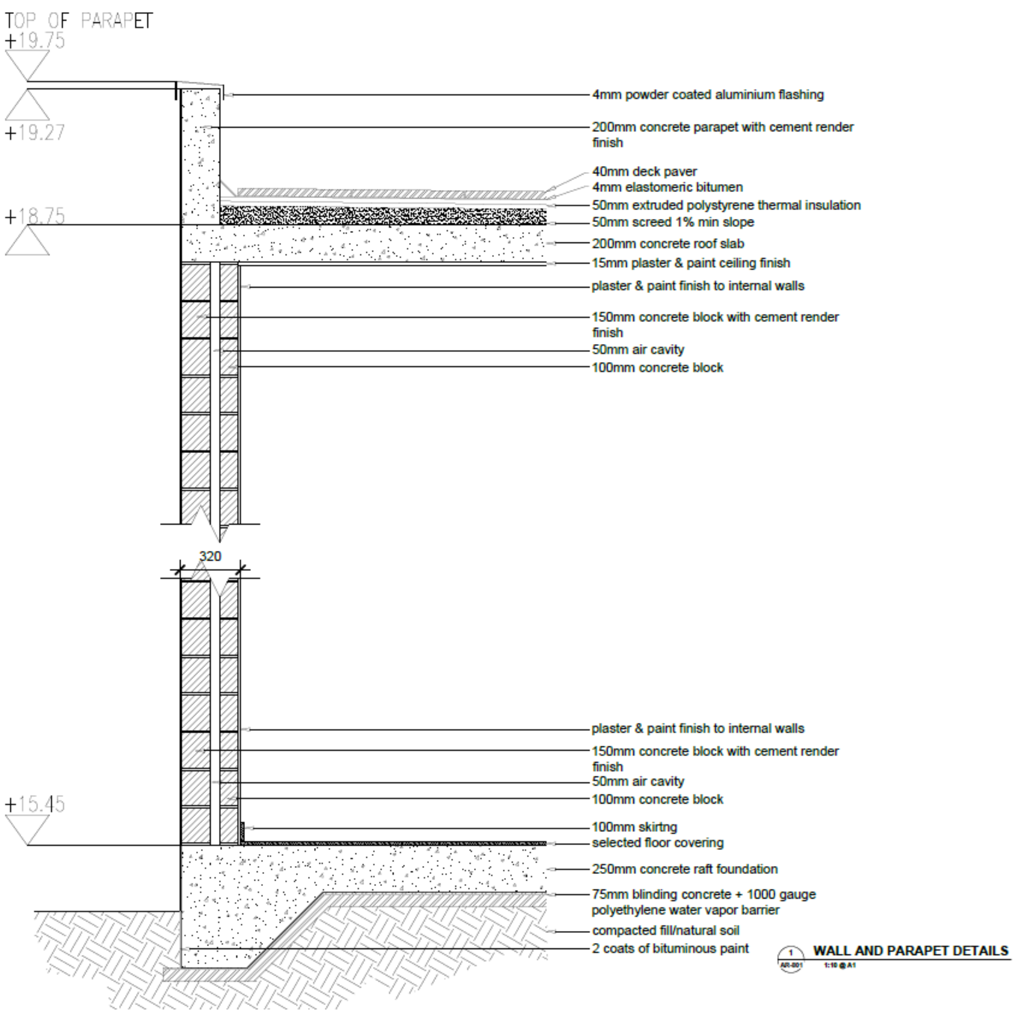


Figure 6-25 STV Wall and roof construction composition

The external glazed surfaces were double-glazed panes with an inert argon gas fill. The parametric study was carried out by applying changes to the STV in three phases. The first phase included upgrading the insulation level of the STV, through the modification of the thermal transmittance levels of the opaque surfaces, to the level of the PHV. The second phase involved optimising the glazed surfaces of the STV in two stages: the first stage incorporated insulating the glazed surface to a level close to the PHV glazed surface insulation, and the second stage fine-tuned the window-to-wall ratio to a level lower than the PHV.

The third phase incorporated a number of further enhancements to the STV. These included integrating additional internal and external shading systems, improving the wall and roof emissivity and solar absorption coefficients, and, finally, altering the type of glazing and insulation in comparison to the PHV. The cooling system, appliances and occupant schedules remained the same. The economic impacts of the parametric study were not included in this study for two reasons. The first was due to the time constrains of this research, and the second to narrow the focus of the study. The three phases are highlighted in Table 6-3, in addition to the base case configuration which is illustrated in the first row. The individual impact of each alteration was first examined and later the combined overall effects were evaluated.

6.5.2 Findings and analysis

The findings indicated that, with the sole improvement of the thermal envelope configuration, the overall performance of the STV was upgraded, but not to the level of the PHV. While a similar replication of the PHV thermal envelope was carried out in the study through the first two phases, other factors including energy-efficient lighting, cooling system and appliances were not added to the study. A significant reduction of total energy and cooling demands was evident through the parametric study.

The percentage of change reached just above 50% and 20% in comparison to the base case scenario in terms of the cooling demand and the total energy respectively while considering the combined parametric scenario. The most significant variation to the building envelope was observed in phase 2-A, where the glazing was upgraded from double glazing to triple glazing. In the individual parametric similarly the impact of changing the glazing to triple glazing has achieved maximum reduction in terms of total energy and the cooling demand (see Figure 6-26). The impact of altering the glazing type was the main contributor towards reducing the cooling loads to almost half in the combined parametric scenario, and to around 20% in the individual impact study. The consideration of solar gains and internal gains were not considered in this case, due to the research focus and the lack of measured data related to this aspect. The total energy use was similarly reduced to around 12% through this variation in the combined scenario; and to around 9% in the individual scenario. As a result of increasing the insulation layer to an extensive insulation layer of 380mm, the cooling demand was reduced by a further 17% and the total energy by 7% in the combined scenario and to 12% and 6% in terms of cooling demand and total energy in the individual scenarios, marking it as the second significant impact on the overall enhanced performance of the STV (see Figure 6-27).

Table 6-3 Variables used for STV parametric study

Phase	Thermal envelope configuration	U-values(W/m^{2}K)
Base model	Wall (**50**mm air gap) - roof (**50**mm extruded polystyrene) – glazed surfaces (double-glazed clear float panes with inert argon gas fill) - WWR (32%)	Wall (1.31) Roof(0.30) Floor (0.50) Glazed surfaces (2.59-2.62)
Phase 1	Wall (**380** mm extruded polystyrene) - roof (**380**mm polystyrene) – floor (**200**mm extruded polystyrene) glazed surfaces (as above) - WWR (as above)	Wall (0.077) Roof(0.087) Floor (0.13) Glazed surfaces (as above)
Phase 2-A	Wall (as above)- roof (as above) – floor (as above)- glazed surfaces (triple glazing with inert argon gas fill l)- WWR (as above)	As above Glazed surfaces (1.28-1.62)
Phase 2-B	Wall (as above) - roof (as above) – floor (as above) - glazed surfaces (as above) - WWR (29%)	As above
Phase 3-A	Wall (as above)- roof (as above) – floor (as above)- glazed surfaces (as above)- WWR (as above)- SRI-100	As above
Phase 3-B	Wall (as above)- roof (as above) – floor (as above)- glazed surfaces (as above)-WWR(as above)- SRI-100- internal & external shading	As above
Phase 3-C	Wall (as above)- roof (as above) – floor (as above)- glazed surfaces (triple glazing with inert krypton gas fill)- WWR (as above)- SRI-100-internal & external shading	As above Glazed surfaces (1.11-1.50)

Phase 3-D	Wall (380 mm polyurethane board)- roof (380 mm polyurethane board) – floor (200 mm polyurethane board)- glazed surfaces (as above)- WWR (as above)- SRI-100- internal & external shading	Wall (0.06) Roof(0.06) Floor (0.10) Glazed surfaces (as above)

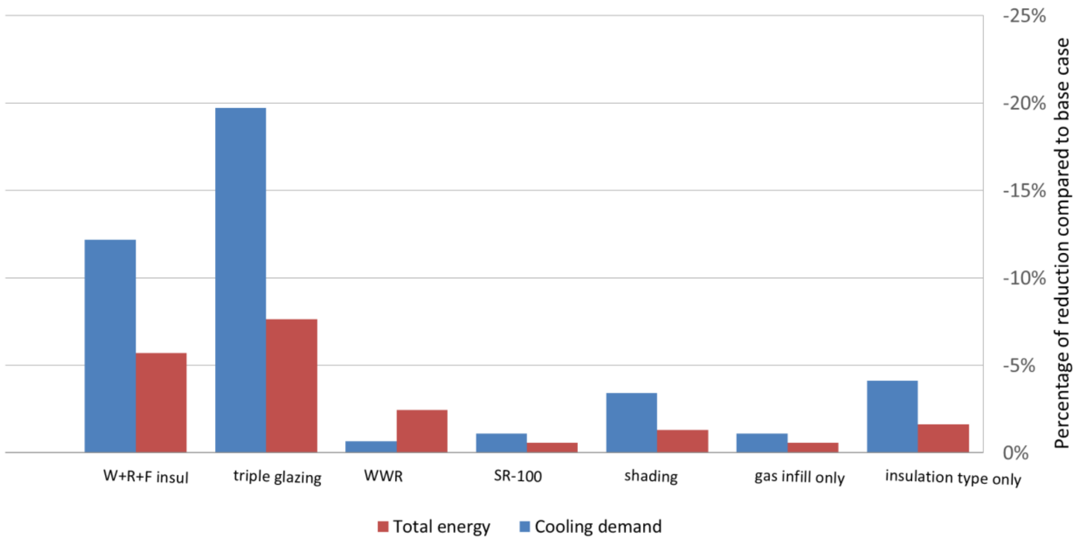
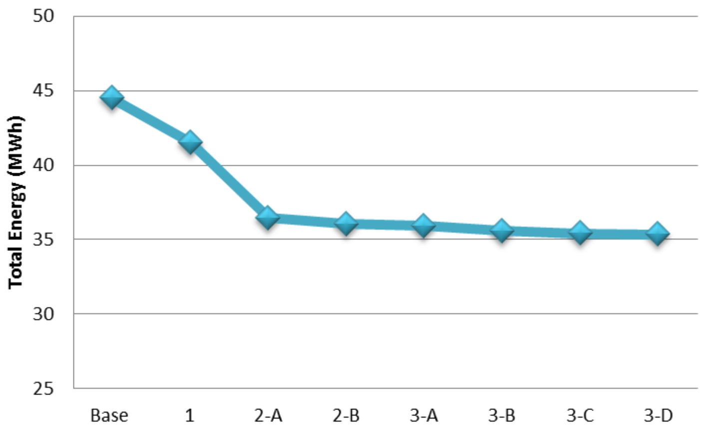
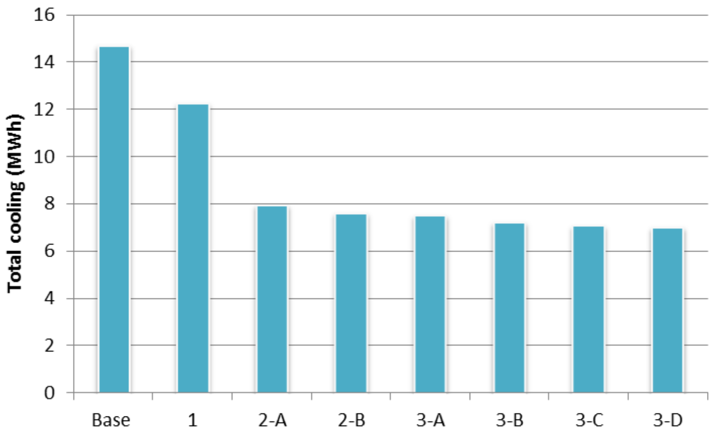


Figure 6-26 Individual effect of parametric variations on cooling and energy demands



(a) Effect of parametric variations on total energy demand



(b) Effect of parametric variations on total cooling demand

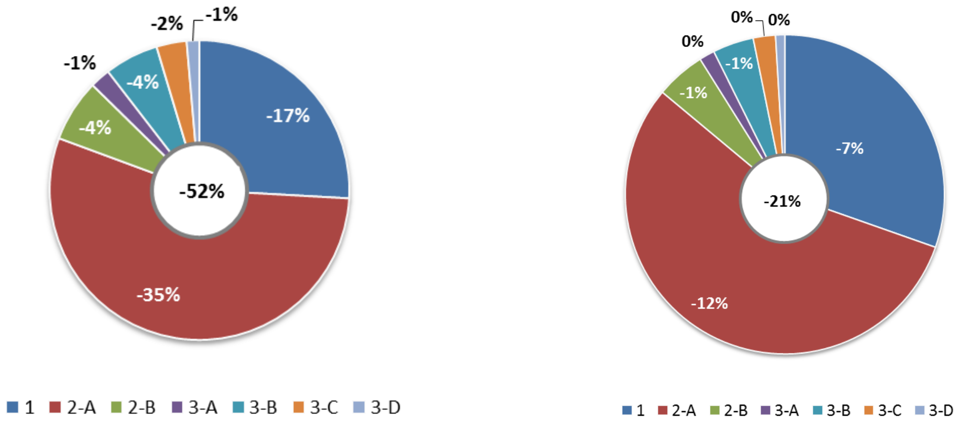
Figure 6-27 Combined effect of parametric variations on cooling and energy demands

Other variations in the combined scenario, such as the WWR, emissivity and solar absorptance, solar reflectance index and the addition of shading systems, have accumulated additional reduction percentages ranging between 0.1% and 4%. The effect of these configurations had variable impacts on the total cooling and energy demands. The variation had a more tangible impact in lowering the cooling demand by percentages ranging from 1% to 4%, whereas the same variations had negligible effects in terms of the total energy demands (0.1% -1% reduction). The two other contributors towards the reduction in the total cooling demand by 4% and total energy use by 1% were found to be the WWR (2-B) and the introduction of additional shading systems (3-B) (see Figure 6-28).

In the individual scenarios these variations had shown slightly variable results. In terms of cooling demand, the introduction of a variable insulation material was the variable with the most reduction in this category at 4%. This was closely followed by the introduction of different shading systems at 3%. The variation of the inert gas and the enhancement of the emissivity and solar absorptance, solar reflectance index showed reduction levels of around 1.1%. Finally the alteration of the WWR indicated a reduction in the cooling demand at around 0.7%.

In terms of the total energy use the reduction of WWR was the variable with the most impact, at a reduction ratio of 2%, followed by a close impact for both the introduction of the shading systems and the variation of the insulation material, with percentages ranging from (2%-1%). Finally the solar reflectance index and the variation of the inert gas introduced reduction of just below 1 % (see Figure 6-26).

As the main objective of the study was to measure the impact of enhancing the STV's thermal envelope to the level of the PHV, additional thermal envelope configurations were not considered. Nevertheless, phase 2-B and phases 3A to 3D of the thermal envelope configurations included variations to the STV envelope exceeding the PHV thermal characteristics, such as the reduction of the WWR, and the alteration of the insulation material used in the wall, roof and floor, in addition to varying the inert gas fill in the glazed surface. The additional changes had a smaller impact in terms of reducing energy and cooling, and further configurations were not added.



(a) Cooling demand percentages of reduction *(b) Energy demand percentages of reduction*

Figure 6-28 Percentages of energy and cooling demand reduction

6.5.3 Parametric study discussion and conclusion

The study carried out in this research was used to upgrade the performance of the STV in comparison to the PHV. The thermal envelope was the main aspect in the upgrading process to bridge the performance gap between the STV and the PHV. The overarching aims of this parametric study were to measure the effectiveness of the PHV thermal envelope and to measure the possible performance enhancements that could be achieved by fortifying the thermal envelope of the STV to the PHV level. Several thermal envelope configurations were used in the parametric study, with the aim of closely matching the thermal transmittance of the opaque and transparent surfaces of the PHV. The impact of the variations was measured in relation to the total energy use and cooling demands.

According to the World Bank database, Qatar's electrical consumption per capita in 2011-2015 was estimated at 15,471 kWh, while, based on another study conducted in Qatar, residential buildings consume around 14,000 kWh per capita annually (Meier, Darwish and Sabeeh, 2013; World Bank, 2016b). Based on the latter figure, for a family of four members, the total energy consumption would be equivalent to around 56,000-61,000 kWh annually. The STV in this study was predicted to consume 44,500 kWh annually, which was estimated at 20%-27% less than the standard residential buildings in Qatar based on the two references cited above. This variation may be due to two reasons – primarily due to the fact that the STV was constructed according to the GSAS rating system. The STV was rated at one star on GSAS, incorporating the use of double-glazed windows and a better-insulated building fabric in comparison to a standard building in the country. Second, the STV is considered a relatively small building in comparison to the residential building stock in Qatar, and both the family size and building footprint may have contributed towards the reduced electricity consumption.

The finding indicated that by insulating the building's opaque and transparent surfaces considerable energy savings could be achieved. The overall possible energy savings in comparison to a standard villa in Qatar could reach around 40% by solely upgrading the building fabric, and to an additional 60% energy saving if reaching the PHV configuration (see Table 6-4).

Table 6-4 Energy demand comparisons for a family of four members

Building type	Total energy demand (kWh)	Percentage of reduction from standard case
Standard buildings	54,000 - 61,000	-
STV (base case) – before parametric study	44,500	21%-27%
STV (enhanced) – based on combined suggested variations	35,400	37%-42%
PHV	21,500	62%-65%

In Qatar, KAHRAMAA, the water and electricity authority publishes building guidelines, including maximum thermal transmittance for walls and roofs, but no actual enforcement of the guidelines is evident. Many buildings in Qatar, specifically in the residential sector, are built without the consideration of the thermal performance of the envelope, and with an overreliance on the cooling systems to compensate for the uncomfortable environments that result.

Although this study only included one aspect, 'the building fabric', it has touched on the importance of treating the outer layers of buildings in the specific climatic zone to achieve energy savings. Other aspects that could be utilised to enhance the overall performance of residential buildings include the use of energy-efficient lighting, appliances and cooling systems. In addition to optimising the building design, such as giving consideration of to the location, and other aspects such as WWR could also be considered during the design stage, in order for buildings to achieve better performances in the future.

While the implementation of a layer of around 400mm of insulation, and the use of triple-glazed windows may not be an economically feasible and attractive alternative to residents in the area, it has proved that significant energy reductions are possible.

Based on this simplified approach, a number of general outcomes could be highlighted that would possibly contribute towards additional energy savings for this specific building:

(1) Upgrading the transparent surfaces' thermal transmittance through the use of high-definition glazing systems,

(2) Enhancing the thermal properties of the opaque surface through the use of the most suitable insulation material to an optimised thickness,

(3) Considering WWR while designing a building,

(4) Incorporating a variation of shading systems, based on the location and design of the building.

Finally, by further optimising the insulation thickness and the configuration of the thermal envelope to levels accepted economically in Qatar, energy savings in the area are bound to be achieved.

6.6 Summary

The energy efficiency of buildings has become a topic investigated by scientists and policy makers at various levels. The importance of addressing this topic arises from its impacts mainly associated with the burning of fossil fuel gas, oil or coal to generate energy. The impact not only affects the respected district or region, but is extended on a global scale to become a threat for the environment which is shared globally by all nations. In addition, non-renewable energy is diminishing and is expected to be replaced by renewable sources of energy to sustain the necessities of daily life for the future. In Europe, several voluntary energy-efficient building typologies have been developed, such as low energy building, zero energy building, eco-house, Passivhaus building, etc. In this research, the voluntary ultra-low energy typology the German Passivhaus standard was assessed for possible application in the hot and arid climate of Qatar. The performance of the Passivhaus buildings in Europe has proved to be successful in several studies, assuring savings in energy, while achieving, in most cases, high thermal comfort levels. However, in a number of studies, issues related to overheating within buildings being built according to the Passivhaus standard in countries other than Germany have been raised.

In 2013, a pilot project was announced in Qatar concerning the first Passivhaus building in the GCC region. The performance of the Passivhaus building in Qatar was investigated in this research to assess how close the building actually came to the performance level of the German Passivhaus standards. Furthermore, the Qatar Passivhaus villa was evaluated against a standard villa that was built according to one star on the recently adopted GSAS rating system in Qatar. Three indicators were used to assess the performance of the PHV against the STV and in accordance to the Passivhaus standard: (1) energy use, (2) thermal comfort and (3) the thermal envelope performance.

The findings indicated that the PHV had closely matched the expected performance of a Passivhaus building in a hot and arid climatic zone. Additionally, the PHV, compared to the STV, had achieved above 50% savings in energy use and an almost 75% reduction in cooling demands at the present time and in the different future scenarios. Both the STV and the PHV had succeeded in achieving acceptable levels of thermal comfort, although the PHV had indicated a better consistency in maintaining thermal comfort at almost identical levels, regardless of the temperature rise associated with climate change impacts in the future timeline series. Furthermore, the PHV adhered to the overheating benchmarks adopted by the Passivhaus standard, although, according to the standard, unacceptable moisture content may be an issue that the PHV may need to resolve in the future.

The extensive layer of insulation in the PHV has created a robust shell that maintains the indoor temperatures at a low level compared to the outdoor extreme conditions. Heat gain had been minimised in the PHV in comparison to the STV, allowing indoor temperatures to be cool at loads lower than would be expected. Finally, a parametric study was carried out to measure the effectiveness of the robust thermal envelope of the PHV. The study was conducted by transferring the features of the PHV thermal envelope to the STV, and examining the extent of the changes on total energy use and the cooling demand on the STV. The results were also cross-referenced with the estimated energy consumption in buildings in Qatar to further assess the impact of enhancing the thermal envelope of buildings in the country. The study indicated that, with the upgrading of the outer fabric of the STV, the total energy consumption could be reduced to around 20% and the cooling demand to around 50%.

This chapter has shed light on the performance of the PHV in Qatar, where field measurement and virtual simulations were used as the main mediums to complete the assessment process. The next chapter will discuss in further detail the implications of the findings and how they relate to the German Passivhaus standard, and to the future of energy-efficient buildings in the region. The first section will discuss the application of the Passivhaus standard in hot climates by discussing the findings of the Qatari Passivhaus project in conjunction with the three case studies presented in the Passivhaus Standard Chapter. The next section will focus on the performance of the PHV in relation to the Passivhaus criteria. The third section will present the challenges envisaged within the building sector as a result of climate change within the region. Finally, the outcomes of the PHV performance will be debated in light of the current practices adopted in Qatar, and how the application of the PHV model and its special features would affect the energy balance in the country's residential sector.

Chapter Seven
Discussion

7 Discussion

7.1 Overview

Energy-efficient buildings are being realised today as the possible solution and the transition towards future-proofing buildings. With the depletion of non-renewable energy sources, and the alarming warnings of climate change impacts, efforts are intensively being directed towards mitigating GHG emissions and achieving savings in energy. In developed countries, a strong research base has been initiated during the last four decades. This has led to the development and widespread use of various types of energy-efficient buildings within developed countries. As a result, future energy targets have been set to include efficient use of energy and a smooth transition to renewable energy sources, such as the EU 20-20-20 target. The 2020 target includes 20% savings in energy consumption, 20% reduction in GHG emissions and 20% increases in renewable energy use. Furthermore, the EU leaders have adopted climate and energy framework targets for 2030, in line with the 20-20-20 energy package targets, incorporating further reductions and savings (European Commission, 2015). On a national level, each EU member has set a number of strategies to achieve reduction in energy use in the built environment, including the introduction of energy-efficient building models such as net zero buildings, zero carbon building and Passivhaus buildings (Pittakaras, 2015). In Qatar, energy targets, according to Meltzer, Hultman and Langley (2014), have been set to include a 7% reduction in energy generation by 2016, and 20% of energy being sourced through renewable energy sources by 2040. Energy efficiency in the built environment has been sought in Qatar through the implementation of the GSAS performance rating system. Since 2012, public buildings in Qatar have been expected to earn a three star score on the rating system; commercial buildings, on the other hand, are to incorporate the rating system by 2016, while residential buildings are to comply by 2020. Applying the minimum GSAS standard is estimated to save around 30% in energy use compared to the conventional practice (Lahn, 2013). However, evidence of applying energy-efficient measures in the domestic sector in Qatar is less tangible. According to correspondence with a research specialist in QGBC, energy conservation policies are not mandatory in Qatar. Even though a number of buildings in

Qatar have actually applied the GSAS rating system, this was only limited to governmental buildings, such as schools, mosques and governmental office buildings in addition to other public projects in the country.

This research, therefore, aimed to address the lack of energy-efficient models in the residential sector by introducing an ultra-low energy model that could be compatible for the climatic conditions of Qatar. The Passivhaus standard has been investigated by many researchers for application in their precise context, either by specifically addressing the Passivhaus standard itself or by addressing its application, leading to other energy-efficient model such as low energy buildings, zero carbon or zero energy buildings (Lynch, 2014; McLeod, 2013; Pittakaras, 2015; Mohammadpourkarbasi, 2015). In this chapter the implication of applying the Passivhaus standard will be discussed in the light of three aspects. The first aspect involves examining the Qatar Passivhaus project in light of the case studies that have successfully adopted the Passivhaus standard and have gained recognition by the PHI or other similar bodies in hot climatic zones. The second aspect discusses the performance of the PHV in conjunction with the Passivhaus standard and the results demonstrated in the previous chapter. Finally, the implications of the implementation of the Passivhaus model in the context of Qatar and the GCC will be highlighted for the present time and the future, and a possible enforcement outline plan suggested.

7.2 Qatar Passivhaus Project vs. Other Passivhaus Projects in Hot Climates

Passivhaus buildings have been built voluntarily in various locations with varying climate conditions. In Part one- Chapter Three, three Passivhaus buildings were presented in hot climate zones, the Austrian embassy building in Jakarta, Le-Bois house in Louisiana and Dubai's virtual model house.

All three physical projects had undergone careful study and consideration in order to achieve the Passivhaus standard. Table 7-1 summarises the key elements of the earlier described Passivhaus projects in addition to Qatar's Passivhaus project.

The fact that all four buildings had integrated PV panels suggests two finding – first, that all projects not only aimed to reach the Passivhaus standard, but had the ambition of becoming nearly zero energy buildings; second, that further decrease in total demands was pursued, possibly as a result of the prolonged cooling season, and the increase in cooling demands.

In addition, it was noticed that Qatar's PHV estimated primary energy demand and the Le-Bois house’s actual primary energy demand were higher than the Passivhaus benchmark, whereas the Austrian embassy’s primary energy demand estimate was in accordance with the Passivhaus criteria, and the Dubai virtual model was even estimated at relatively low primary energy demand. In comparison to the three residential projects, the larger scale embassy building – which housed a larger number of inhabitants utilising more equipment and lighting, suggesting an expected increase in internal gains – was actually estimated with a similar primary energy demand to the Le-Bois house, and with less demand than Qatar’s PHV. This suggests that the exclusion of a conventional air-conditioning system had attributed considerably to the reduction in primary energy demands in the Austrian embassy.

Other aspects that were taken into consideration in all projects were the glazed surfaces and the treatment of the outer shell. Glazed surface location and shading were consistently highlighted in the four projects. Windows were mainly oriented towards the north-south, with shading elements projected onto the roofs of the buildings. In the case of the Dubai model, windows were completely eliminated from the outer shell and were minimised to the extent required to provide sufficient daylighting. Low-e double or triple glazing was used in all the projects, with various inert gases such as krypton in the case of the Le-Bois house, and argon in Qatar’s PHV.

A well-insulated outer envelope was highlighted in the four projects. Qatar's Passivhaus exterior wall was almost 570mm thick with a 380mm thick insulation layer. The Le-Bois house external wall was composed of 85% of insulation and only 15% of timber studs, thereby achieving very low U-value levels.

Table 7-1 Features of the four Passivhaus buildings

Project / criteria	Austrian Embassy	Qatar PHV[1]	Le Bois House	Dubai model
Building type	Non-Residential[2]	Residential[2]	Residential[2]	Residential[3]
Construction type	Masonry	Masonry	Timber	Masonry
Floor area	1000 sqm	200 sqm	120 sqm	295 sqm
Construction year	2011	2013	2010	-
Air tightness @ 50 P	0.45	0.9	0.55	0.6
Estimated Cooling demand (Kwh/m^{2}a)	-	23	15/10.6[6]	32
Estimated heating demand (Kwh/m^{2}a	-	-	8.0/0.6[6]	-
Estimated Primary Energy (Kwh/m^{2}a)/ Measured	117.1	135/78[4]	116/184[6]	87
Opaque surface U-value (W/m^{2}K)	R[5](0.11)-W(0.32)-F(0.29)	R[5](0.08)-W(0.08)-F(0.119)	R[5](0.018)-W(0.04)-F(0.06)	R[5](0.196)-W(0.122)-F(0.196)
Glazing type	Double glazing	Triple glazing	Double glazing	Triple glazing
Solar Panels use	√	√	√	√
Cooling strategy	Passive	Mechanical	Mechanical	
Dehumidification	√	-	√	√
Solar water heater	√	√	-	√
Other	-	Grey water	-	Grey water

1 Based on IES-VE results
2 Physical building under monitoring
3 Virtual model
4 Based on three sub-meter readings without occupancy
5 R: Roof, W: Wall, F Floor
6 Actual measured use

The cooling demand of the buildings varied – the Le-Bois house achieved an estimated cooling demand of 15 kWh/m^{2}a, although the actual measured cooling demand was 10.6 kWh/m^{2}a, while for the Dubai model the peak cooling load was met at 10 W/m^2; however, the cooling demand was estimated at 32 kWh/m^2. The current Passivhaus criteria cooling demand need not be limited to 15 kWh/m^{2}a, but can vary based on the climate, internal heat, moisture and air change rate. Additionally, de-humidification requirements have been added to the specific cooling demand calculation, allowing a further increase in the cooling demand compared to the previous 15 kWh/m^{2}a limit.

The German Passivhaus standard is becoming a subject of interest to architects, engineers and building scientists. Its success and wide spread have resulted in an increased amount of studies and experiments related to its flexibility and adaptability in varying climates and conditions. The number of Passivhaus projects outside Europe is increasing, but the feasibility of these projects and their success are yet to be evaluated and examined. Dynamic simulation tools and energy balance sheets present indicators of the expected performance of any project. Although the initial estimations and predictions of many Passivhaus projects outside Europe seem to be promising, the actual test would be putting these projects under examination by physically monitoring their performance.

Passivhaus projects have been built and realised in hot and humid/arid climates, but the success of these projects may be governed by a number of factors:

1. The actual performance of the building,
2. The actual comfort levels of the occupants,
3. The effect of users' behavioural patterns within a Passivhaus project,
4. The feasibility and ease of construction based on Passivhaus techniques,
5. The cultural acceptance of the Passivhaus standard stringent construction requirements.

The three showcased projects were physical examples that would conclude the success story of the Passivhaus standard outside its native lands. Monitoring and continuous reporting are the sole means of identifying the actual success and feasibility of achieving Passivhaus standards in hot climates.

7.3 Qatar Passivhaus Performance vs. the Passivhaus Criteria

Through the assessment of Qatar's Passivhaus project, and the comparison to other Passivhaus projects in hot climates, it is evident that Passivhaus buildings are achievable in hot climates. However, not all buildings had actually met the stringent Passivhaus standard. The Le-Bois house and the Qatar PHV, for example, were close to reaching the standard, but they mainly failed to reach the primary energy demand target (see Table 7-2). Nevertheless, the buildings have been proved to deliver a high performance compared to standard or even low energy buildings, such as the comparison of the PHV against the STV presented in this research in terms of energy use, thermal comfort, and the thermal envelope performance.

Table 7-2 Qatar Passivhaus villa vs. Passivhaus standards based on IES-VE results

Criteria	Passivhaus standard	Qatar PHV
Specific primary energy demand(kWh/m^2)	≤120	135/(-186)[1]
Specific cooling demand (kWh/m^2)	≤ 27	23
Overheating frequency (% of time operative temperature above 25°C)	10/0[2]	0
Moisture level limit (% of time moisture content above 12 g/kg)	20/10[2]	3
Opaque surfaces' U-value (W/m^{2}k)	0.25	0.08
Transparent surfaces' U-value (W/m^{2}k)	1.0-1.20	0.8
Air tightness (@ 50 Pa)	≤ 0.6	0.9

1 Negative energy demand as a result of excess energy generated through PVs
2 Without active cooling/with active cooling

The importance of addressing energy-efficient models for Qatar and the GCC region arises from the fact that the residential sector lacks energy-efficient measures. Houses have been built either with no insulation or with insulation levels meeting the maximum U-value required, which are relatively unacceptable compared to the Passivhaus standard for this specific climate zone. In the case of Qatar, KAHRAMAA building guidelines indicate the maximum U-values for residential and commercial buildings. The maximum U-values are 0.437 W/m^{2}K and 0.568 W/m^{2}K for the roof and wall respectively. Glazed surfaces have a maximum U-value of 3.30 W/m^{2}K for WWR of 5% - 40%, and 2.10 W/m^{2}K for WWR above 40%; double glazing is only required for commercial buildings, such as showrooms.

According to the Passivhaus climate zone certification criteria (see Figure 7-1), Qatar falls within the "very hot "climate classification. Based on the criteria for this specific zone, opaque surface are expected to achieve a U-value of 0.25 W/m^{2}K for the external building component, and 0.3W/m^{2}K for building components in contact with the ground (PHI, 2015b). Glazed surfaces in this climate are expected to achieve U-values of 1.0 W/m^{2}K for vertical glazed surfaces, 1.10 W/m^{2}K for inclined glazed surface, and 1.20 W/m^{2}K for horizontal glazed surfaces. According to the Passivhaus criteria, this could be realised by using solar control triple glazing with a high precision in selection (PHI, 2015c) (see Table 7-3).

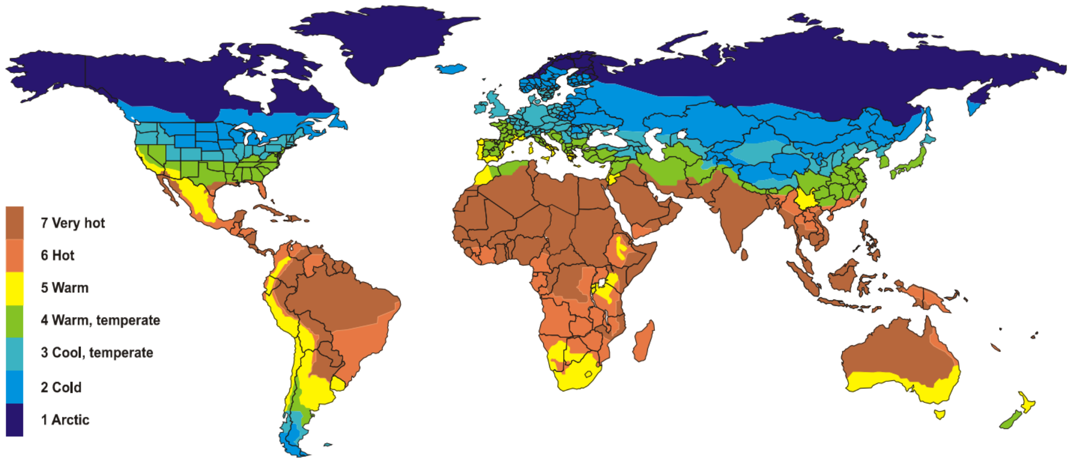


Figure 7-1 Passivhaus climate zones (PHI, 2015a)

Table 7-3 Opaque and transparent surfaces' U- values (adapted from (KAHRAMAA, *2016; PHI, 2015b; PHI, 2015c))*

Standard	U- values (W/m2K)				
	Wall	Roof	Floor	Windows	Recommended glazing type
Passivhaus Standard	0.25	0.25	0.3	1.0-1.20	solar control triple glazing
Qatar's KAHRAMAA building guide	0.568	0.437	-	3.30 - 2.10	Double glazing for commercial buildings

7.3.1 Energy use

In terms of energy use, the PHV was estimated, in the present-day scenario, to consume around 135kWh/m^{2}a, a 12.5% increase compared to the Passivhaus primary energy demand benchmark. The future scenarios indicated a further divergence from the Passivhaus benchmark, predicted at an increased percentage of 25%, 34% and 50% for the 2020, 2050 and 2080 timeline scenarios respectively. Compared to the STV, however, the PHV required almost 60% less energy to operate for the three future timeline scenarios. Additionally, the whole demand of the PHV could be met through the energy generated via the PV panels. The measured energy use while the house was not occupied indicated that the HVAC system, lighting and casual use of other small power appliances was measured at 78kWh/m^2; this figure includes the major expected contribution towards energy use in the PHV, i.e. the HVAC system. However, without the villas being occupied, the figure is not totally reliable. Furthermore, the initial simulation using the PHPP balance sheets indicated that the specific primary energy use is estimated at 106kWh/m^2, but it should be noted that best practices have been considered, and that the actual systems, lighting, appliances and auxiliary equipment were not a replication of the PHV case, due to the absence of technical data required (see Table 7-4).

Table 7-4 PHV estimated and measured primary energy demand

PHV estimated PE (IES-VE)	PHV measured PE[1]	PHV estimated PE (PHPP)[2]
135 kWh/m^2	78 kWh/m^2	106 kWh/m^2

1 Without occupancy
2 Based on best practices, not actual case

An issue that could come into question at this point concerns the Passivhaus primary energy demand criteria for the future. Buildings are expected to consume more energy as a result of the inevitable climate change impact. As outdoor temperatures are expected to rise, more demand will be exerted on mechanical cooling systems in hot climates, and similarly in cooler or moderate climates. Buildings that today meet the primary energy demand and cooling demands of the Passivhaus standard may not do so for future change. Should a coefficient for future primary energy use be introduced, or should a continuous upgrade of the Passivhaus criteria be carried out by the PHI, to ensure buildings are consuming less energy in conjunction with the trajectories of the future? Or would the robust building envelope safeguard the building for the future climate change impact? It could be argued that the building appliances, equipment, lighting and HVAC systems have a lifespan that is shorter than the building's lifespan. With advances in technology, an introduction of even better energy-efficient systems is possible in the future, but would that be enough to maintain the primary energy and cooling demand at Passivhaus levels in hot climates?

Energy-efficient buildings are the answer to future-proofing buildings in the GCC area. Residential buildings in Qatar today are mainly dependent on electricity to operate; however, the energy balance is expected to change, with more reliance being directed towards renewable sources and more specifically solar energy as the main abundant resource in the region.

The design of the PHV in Qatar incorporated the use of solar energy, and exemplified through simulation and measured data, to a certain extent, that the system was actually capable of covering the whole load of the PHV. The PHI had recently introduced renewable energy sources in its certification criteria, by presenting classifications based on renewable energy sources, thus providing an answer to the transitional phase between fossil fuel and renewable energy. The new criteria included low primary energy (PE) use, in addition to primary energy reduction through renewables (PER), thus energy sources in the new Passivhaus criteria are no longer solely provided through non-renewable means.

Furthermore, with the diminishing of fossil fuel resources, renewable energy sources will most likely replace fossil fuel to ensure that humans maintain the sophisticated standards of living they have reached today. The consistent development and evolvement of the Passivhaus standard in accordance with everyday changes has been accounted for in this area; as stated above, this was achieved by recently updating the criteria to include the fuel of the future.

7.3.2 Thermal comfort

The thermal comfort of the occupants of the PHV and the STV was measured using two approaches; the first incorporated on-site measurements through the use of data loggers that measured the indoor temperature and relative humidity levels. The second approach included the use of two thermal comfort models, the PMV thermal sensation and Schnieders' thermal comfort chart.

On-site measurements were carried out during the hottest months of the year in Qatar (June/July) for the three bedroom spaces and the living room in the two villas. A second logging period was considered for the living spaces only in both villas due to the erratic readings revealed through the first logging period. These readings were recorded during the end of the summer season throughout to part of the cold season.

The findings indicated that a thermally comfortable environment was maintained in the PHV. The indoor temperatures were persistently below 25°C during the two logging periods, with the exception of the LIV, where erratic readings were found during the first logging. The relative humidity levels in the PHV were similarly maintained between the 40% to 60% band, although, during the second logging, the RH level in the PHV reached 75% during the month of January. In the STV, the level of consistency was not maintained in all spaces; variable results were found in relation to the indoor temperatures and relative humidity when compared to the predicted indoor environment. The measured indoor temperatures were found to peak during mid-day at variable levels. Higher recorded temperatures compared to expected temperatures were evident during June, while lower than predicted temperatures were found in July. The measured relative humidity levels were much higher or lower than predicted, in both logging periods. Therefore, a lower level of confidence in terms of the on-site measurement findings was evident in the STV in comparison to the PHV.

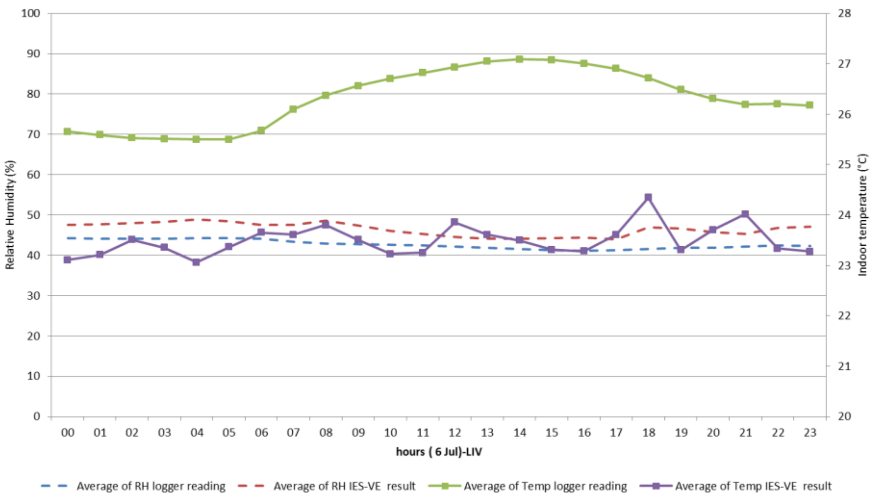
During the hottest day of the year, the 6th July, results indicated that the PHV indoor air temperature was within the expected range – it had even been lower than expected. The temperatures recorded in all living spaces were one to two degrees lower than expected. In terms of relative humidity, the predicted relative humidity levels and the measured levels showed very close proximity. In the STV on the other hand, there was no apparent consistency. During the hottest day of the year, variable results were found while comparing the predicted to measured indoor temperature. With the exception of the LIV readings, which were classified as erratic readings, the bedroom spaces showed variable results the M BR readings were higher than predicted, while lower measured indoor temperatures were evident in BR 1; however, in BR 2, close proximity was found. Relative humidity levels were, on the other hand, of close proximity in the two single bedroom spaces BR 1 and BR 2, while variable outcomes in the M BR were evident: the measured relative humidity levels decreased throughout the day compared to the expected relative humidity levels (see Figure 7-2 and Figure 7-3).

This variation may have resulted from a number of factors; it may have been partly as a result of the accuracy level of the data loggers, which was ± 0.35°C for temperatures ranging from 0°C to 50°C and ±2.5% for relative humidity levels ranging from 10% to 90% RH. It could also be possibly due to manipulation of the set point temperature in the villas, or due to the nature of the outputs from the dynamic simulation tools, which are governed by input data that involve close replication of the actual built environment, such as the use of weather files, building systems, and thermal characteristics of the building materials and occupancy patterns. Nevertheless, the close proximity indicated that the dynamic simulation was reliable to a considerable extent in replicating the indoor environment of the PHV.

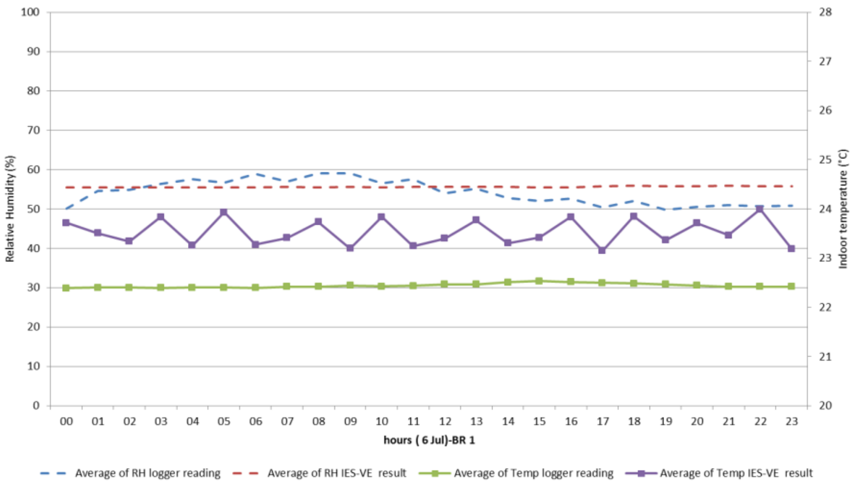
Based on the indoor temperatures recorded and according to research (Al-Sanea and Zedan, 2008; Moon and Han, 2011; Wang, Zhang and Xia, 2013), possible reductions in energy are achievable by simple measures, such as increasing the set point temperature to higher levels. Assuming that the logger readings were accurate, a further reduction in energy is therefore possible in the PHV as a result of the reduced measured temperature, which was on average 22.0 °C-22.5°C.

The thermal models associated with measuring thermal comfort had indicated that a consistent level of thermal comfort was achievable in the PHV. The PMV thermal sensation of the occupants within the bedroom spaces was limited between the thermal sensation band of (-0.5, +0.5), in the living space thermal sensation was predicted to be slightly higher reaching to around +0.7, but not reaching +1.0, which is denoted as a slightly warm sensation. A similar finding was evident for the different timeline scenarios in the PHV, where the thermal sensation was limited to the neutral band, i.e. the thermal sensation of occupants was expected to be below +1.0. Schnieders' thermal comfort chart equally confirmed that thermal comfort could be maintained at a steady level throughout the different timelines. In the STV, on the other hand, according to the PMV thermal sensations, slightly warmer sensations are expected in the LIV space during the three timelines. Based on Schnieders' thermal comfort chart, thermal comfort is extended along the inner thermal comfort zone, the extended comfort zone and beyond.

A realistic approach, however, towards the actual thermal sensation of the occupants was absent in this research; this was, as stated earlier, a result of the villas being unoccupied. It should be noted, however, that in the near future the villas may possibly be occupied by a single researcher, rather than a family as scheduled.

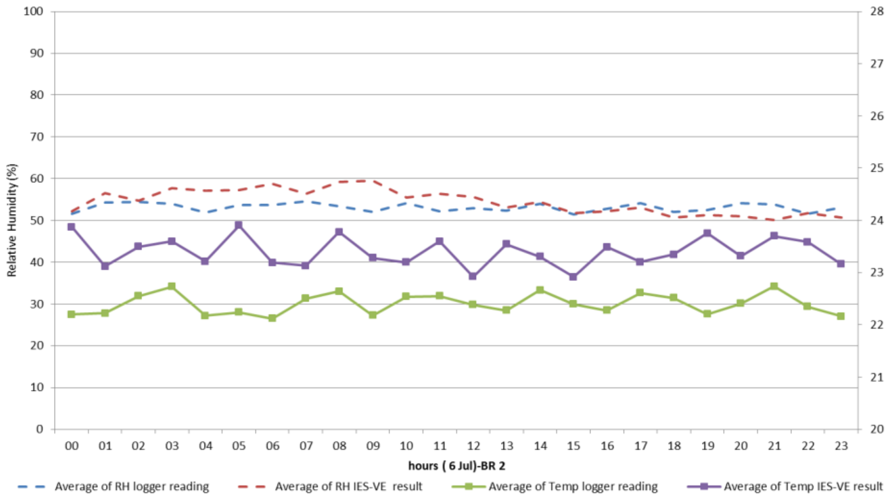


(a) LIV

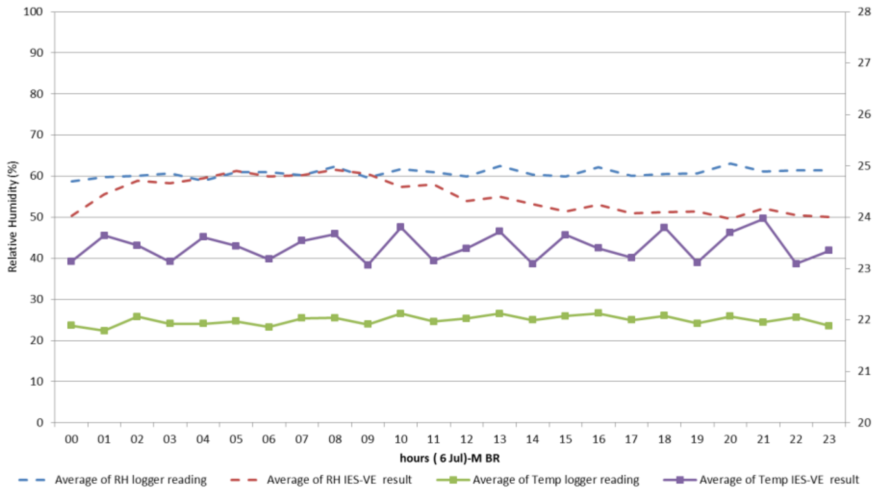


(b) BR 1

Figure 7-2 Measured and predicted temp and RH in the PHV during the hottest day

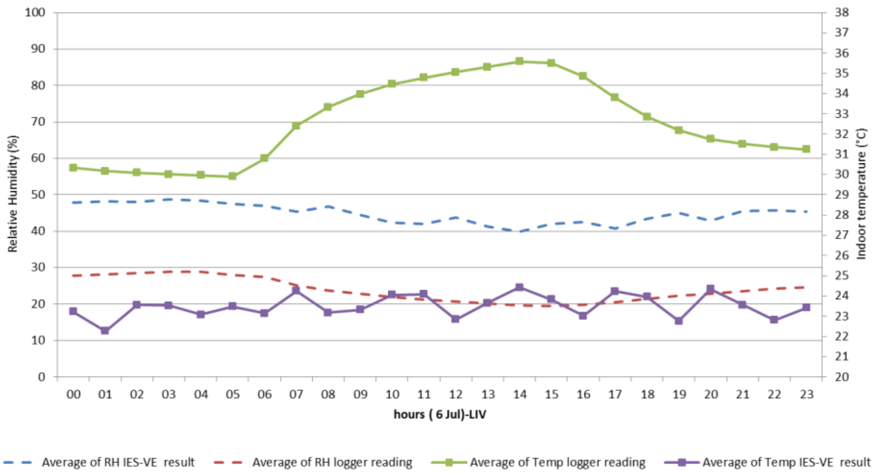


(c) BR 2

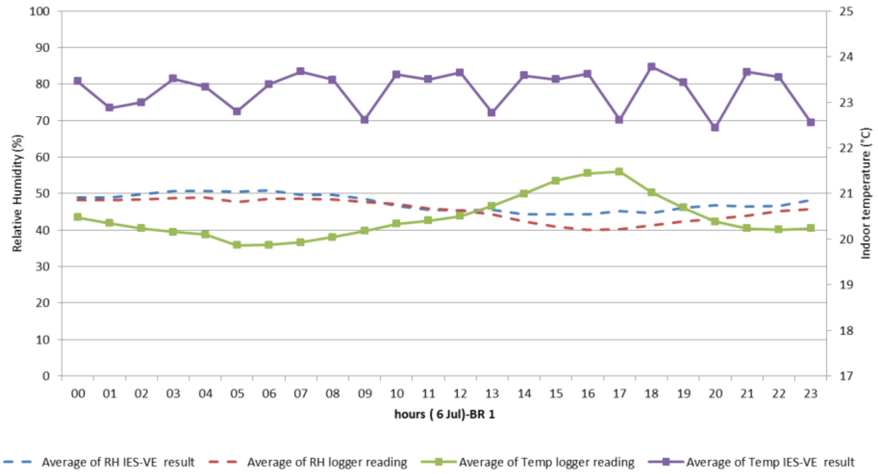


(d) M BR

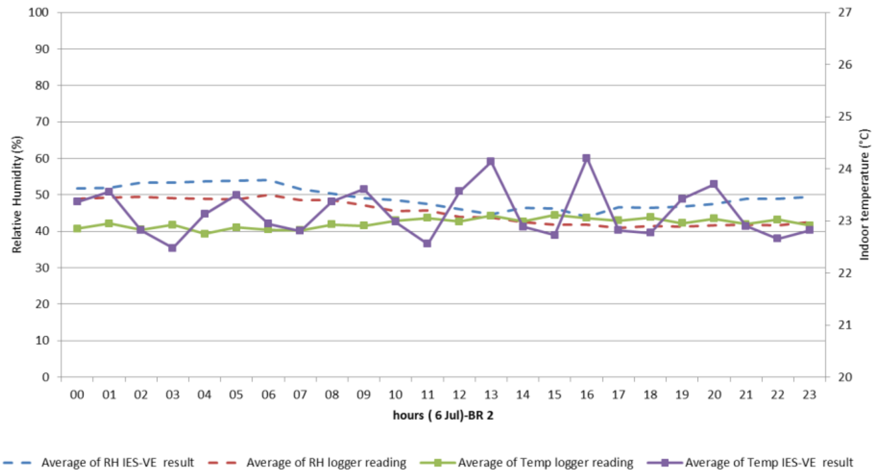
Figure 7-2 Measured and predicted temp and RH in the PHV during the hottest day



(a) LIV

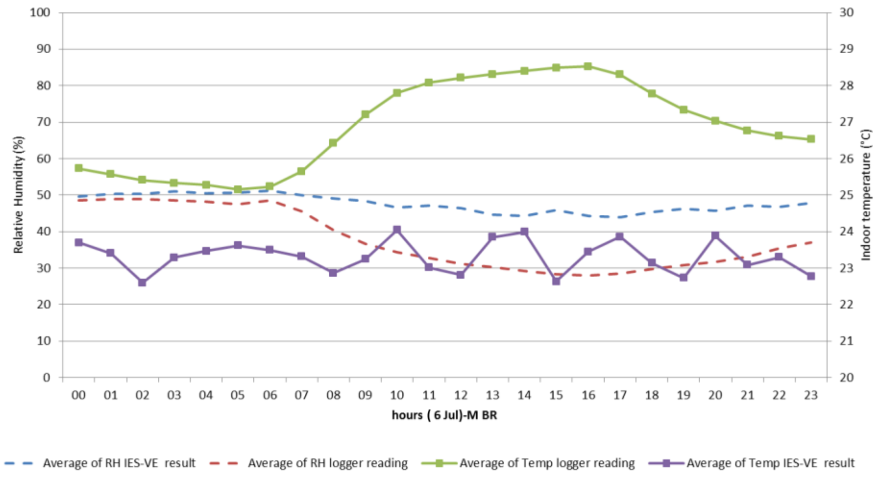


(b) BR 1



(c) BR 2

Figure 7- 3 Measured and predicted temp and RH in the STV during the hottest day



(d) M BR

Figure 7-3 Measured and predicted temp and RH in the STV during the hottest day

According to the Passivhaus thermal comfort criteria, actively cooled Passivhaus buildings should maintain the indoor temperature below 25°C all year round, and air humidity levels should not rise above 12g/kg for more than 10 % of the hours within a given year in the case of using active cooling. Based on the IES-VE findings, the PHV seems to be more likely to suffer from unacceptable moisture levels, at 11%, 12.7% and 24.5% of the time in a given year above 12 g/kg for the years 2020, 2050 and 2080 respectively. The STV, however, showed acceptable moisture content level and much reduced expected moisture for the different time series, at 1%, 4.6% and 13.1% for the 2020, 2050 and 2080 scenarios respectively. The findings suggest that dehumidification is needed for the PHV, although the present-day scenarios indicated that this is not necessary at present, as moisture levels were predicted at 3% above the 12g/kg limit. A number of studies have pointed out that moisture content may be associated with airtight buildings, if mechanical ventilation is not incorporated into the design (Giuseppe, 2013). In Qatar's PHV, a mechanical ventilation system was incorporated with a heat recovery efficiency level of 85%. Dehumidification, however, was not considered in the model. Yet, while attempting to use the PHPP, excess moisture levels were indicated in the PHV for the present-day Qatar climate, and dehumidification was required for the specific building to realise the Passivhaus criteria in Qatar's climate.

7.3.3 Thermal envelope performance

The evaluation of the thermal envelope performance of the PHV was carried out in this study through two measures. The first measure was introduced as part of the assessment of the Qatar Passivhaus performance, and the second as part of the parametric study carried out to upgrade the STV.

Based on IES-VE findings, the indoor temperatures of the PHV were maintained below the extreme mean outdoor air temperatures while active cooling was disabled. This was true for current weather data and the three future timeline scenarios, and during the hot season. In comparison, the STV indoor temperatures were expected to be above the mean outdoor dry bulb temperature for most of the year. This finding suggests that the PHV building envelope was one of the main contributors that aided in the reduction of heat transfer through the building fabric. Solar protection was also considered, and the large fenestration and whole roof were fully shaded by the photovoltaic array.

Additionally, the importance of the outer fabric was assessed through the parametric study conducted on the STV to bridge the performance gap between its performance and the PHV. The study showed that the most significant parametric impacts were associated with the upgrading of the transparent and opaque surfaces. Finally, during the attempt to use PHPP, the building fabric – and most specifically for the case of the PHV geometrical layout and building assemblies, the glazed surface, and absorption levels of the walls and roof – had contributed significantly in reducing the cooling demands in the PHV model.

By fortifying the building envelope, cooling or heating demands could be met at lower energy loads, and ultimately this leads to further conservation of energy. Research carried out in the areas of energy-efficient buildings and strategies has continuously stressed the importance of addressing the outer fabric. Both opaque and glazed surfaces are responsible for improving the indoor thermal environment. Glazed surfaces become of most importance based on the WWR as they are considered the weaker component of the buildings. Additionally, airtightness has been associated with well insulated buildings, not only in the Passivhaus standard, but as a general rule to obtain energy efficiency in buildings (Iannaccone, Imperadori and Masera, 2014). This leads to the conclusion that, in order to reduce cooling loads in buildings within hot climates, and to reduce the impact of the outdoor environment on the built environment, more attention should be given to the outer fabric configuration. Building regulations should be revised, perhaps not to the extent of the Passivhaus standard at this stage, but at least to introduce measures that further effectively shape the outer fabric of residential building in the area. Research in the area of the outer fabric role in reducing cooling loads and energy is continuous. With the emergence of new technologies and materials, the outer fabric could be considered as an active building membrane, rather than a static fabric. Research into relevant various areas, such as the role of dynamic building insulation material, has been undertaken in the region (Elsarrag and Alhorr, 2012), and with further research it would be possible to enhance the building fabric to be more effective in the built environment.

7.4 The impact of climate change on the building sector in Qatar and the GCC

In the past few years the GCC countries have experienced an exceptional economic boom and demographic growth. This has resulted in an extended increase within the building sector, specifically in the UAE (Sabie, Pitts and Nicholls, 2014). In Qatar a similar growth was witnessed as building increased by 50% during the period from 2004-2010, additionally, infrastructure projects are heavily underway in the state (Alhorr and Elsarrag, 2015).

The GCC countries are highly dependent on oil and gas as their main source of energy, although most recently efforts have been recognised to include other sources of energy such as solar energy and non-fossil sources (Reiche, 2010; Munawwar and Ghedira, 2014). The green movement act that has spread through the region over the past 10 years indicates that a higher level of awareness would be anticipated in the coming years in terms of sustainability and energy conservation and diversity (Willis, 2015).

Climate change in considered one of the main future threats in the region, especially that the region is classified as a hot and arid climatic zone. This implies that in addition to the energy dilemma, other social, economic and ecological impacts are expected, affecting land, water and the ecosystem in the area. This includes the upsurge of impacts such as, pollution, scarceness of rain, the flooding of coastal areas and desertification which would be likely expected for the future in the region, marking the region as highly vulnerable to the impacts of climate change (Bhutto et al., 2014).

The GCC countries are expected to endure a temperature rise ranging between 2.5 and 5°C by the end of the century based on a mixed fossil fuel and non-fossil fuel energy sources scenario. The temperature rise for the period between 1901 to 2005 in the Persian Gulf (Arabian Gulf) was recorded between 0.5-1.1°C. Summer mean temperatures are expected to exceed 40°C in the region, thus suggesting an increased demand on the cooling systems (Jentsch, James and Bahaj, 2010).

Additionally, with the prediction of increased temperatures in the GCC cities are expected to adapt to the *'heat wave'* by introducing measures that provide shade, shelter and coolness, not only for buildings but also for other services such as school yards, and construction sites …etc. The use of Air-conditioning is expected to steadily increase especially for outdoor facilities, such as transportation points and similar spaces. This is more likely to result in more energy use or the restriction of outdoor spaces usage. Furthermore, the urban fabric of the city would have to be weaved to introduce shaded and cooled areas. This could include strategies such as the use of evaporative cooling where applicable, or the return to the trends illustrated in the traditional architecture of these cities, such as using thick building blocks that utilised heat storage, small openings and projected balconies that provide shade to the narrow pathways...etc. (Pitts, 2015).

Adaptation and mitigation strategies are being realised today as the means to reduce the impacts of climate change, through the reduction of GHG emissions (IPCC, 2015; Jentsch, Bahaj and James, 2008). Energy conservation and policies within the building sector have therefore become an established strategy to reduce GHG, owing to this sector share in the total global energy consumption (Laustsen, 2008; IEA, 2015).

A number of studies have been carried out in the area examining the path towards achieving reduction of GHG emission through energy efficiency measures. In a recent study carried out for the Middle East and North Africa region (Krarti and Ihm, 2016) a number of energy-efficient measures were investigated to examine the most cost-effective for the region. According to the study, GCC countries could realise around 55% of energy saving through implementing 6 measures; this includes:

1. Introducing roof insulation of around 2cm
2. Reduction of WWR to 10%
3. Utilizing low-e glazing
4. Achieving low levels of infiltration
5. Incorporating high efficiency appliances, lights and cooling systems
6. Increasing set point temperatures to 26°C

To assess the impact of future climate change on residential buildings, this research investigated the future performance of the PHV. The summer mean annual temperature was predicted to increase from 37°C in the present day scenario to around 41°C for the 2080 scenario considering a high to medium future scenario. The analysis of the future performance of the PHV has indicated a continued pattern of energy efficiency through the implemented measures. The measures that been incorporated in the design of the PHV, included; (a) a highly-insulated airtight shell, (b) high definition glazing, (c) high efficient lighting, appliance and cooling system, (d) fully shaded roof, walls and openings, (d) PV panels, and (e) grey water system.

The later mentioned measures have ensured that the building shell maintains indoor temperatures well below the extreme outdoor temperatures; this was evident through the assessment of the performance of the thermal envelope performance. The building shell had also aided in reducing the cooling loads to around at least 4 times less than the STV in the present day, and around 5 times less in the 2080 future scenarios (see Table 7-5).

Table 7-5 PHV and STV estimated cooling loads

Cooling load (kWh/m^2)	current	2020	2050	2080
PHV	23	24.9	28.8	34.9
STV	95.7	114.7	156.1	190.6

Furthermore, the total energy use in the PHV was expected to be at least 50% less than the STV total energy use throughout the present day and the future scenarios (see Figure 7-4).

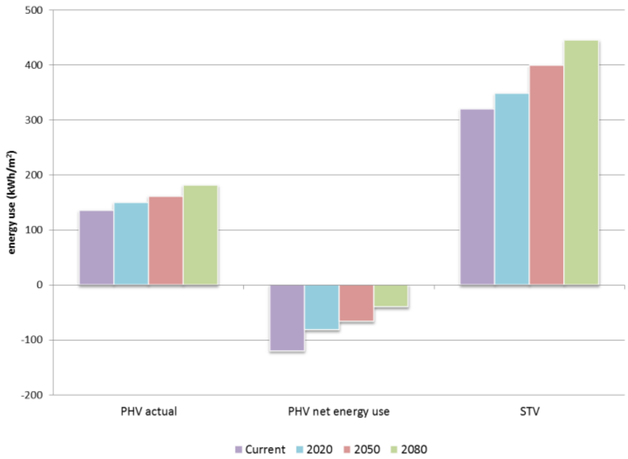


Figure 7-4 Total energy use in the PHV and the STV through the different scenarios

Finally, through the examined indoor temperatures and relative humidity levels, the PHV indoor temperatures are expected to be more consistent throughout the different scenarios as have been illustrated in the previous chapter.

In light of the above-discussed subject, it is evident through the literature that Qatar and the GCC countries are bound to face a number of challenges in the future as a result of the climate change impact, and more specifically in terms of the predicted increased temperatures. This alone would pose rethinking the way buildings and cities are shaped in the future. Today, as we have become more aware of these threats, both building design and the overall conception of energy use within them should be altered to prepare for the inevitable temperature increase. If buildings continue to be constructed without consideration of energy-efficient measures, and if governments and consumers continue to neglect the importance of energy conservation, the building stock of the future will be poorly prepared for the *'heat wave'*. Future-proofing buildings and the assurance that they live up to their intended design expectations is the sole means to achieve energy savings and reductions in GHG emissions. Moreover, the use of clean sources of energy should go hand in hand with the building stock of the future, therefore the PHV example provides a promising prototype for the future of residential buildings in the area.

7.5 Realising Passivhaus Standards in Qatar, Implications, and Key Features

The last three decades have witnessed an accelerating economic, demographic and urban growth in all GCC countries, including Qatar. This has contributed radically towards an increase in energy demand in the built environment, especially the residential sector (Krarti and Ihm, 2016). Despite the presence of standards and building guidelines, their enforcement in not clearly evident in the residential sector. Mandatory enforcement, however, at present is more evident in the government sector (Alalouch, Saleh and Al-Saadi, 2016). Challenges to improving the energy efficiency in the residential sector arise from a number of factors, such as economic, cultural and lack of expertise and skills. Most notably, energy in the GCC is highly subsidised; the average rate for electricity based on 5000 kWh of consumption ranges from 0.007$/kWh to 0.080$/kWh, with Qatar's average electricity rate estimated at 0.022 $/kWh (Krarti and Ihm, 2016). This is accompanied by non-mandatory enforcement, which had led to less interest from consumers to contemplate energy-efficient homes. This could be considered as one of the main obstacles that may face the implementation of the Passivhaus standard in Qatar, and in fact any other energy-efficient model in the region. Whilst the continuous use of active cooling systems has resulted in acceptable levels of thermal comfort in building in the region, it is not feasible from a sustainability or energy conservation viewpoint. Additionally, the reduced energy tariffs have contributed towards directing consumers away from comprehending the importance of energy conservation.

By virtue of implementing energy-efficient measure, additional costs are foreseen and, without economically justifying the added costs, end users may not regard the shift to energy-efficient buildings as advantageous. More awareness, therefore, should be spread in the region with regard to the importance of energy conservation. In addition, building regulation should be revised to become more stringent to ensure effective energy conservation that would withstand future impacts of climate change. The enforcement of the revised building regulations should similarly be re-visited; building regulations should probably become mandatory in the residential sector to effectively guarantee the shift to energy-efficient buildings in the built environment for new builds and retrofits.

Applying the Passivhaus standard has further implications; the highly stringent standard is not as near to any practice led in the region. As demonstrated in the previous sections, the KAHRAMAA building guidelines are not comparable to the Passivhaus standard. Additionally, the implementation of the standard is associated with the acquisition of knowledge that is specific to this standard. In Europe, the standard has spread widely through the associated national Passivhaus bodies in each European country to further promote practices and knowledge about the Passivhaus standard in the specific context. The lack of such organisations, along with training programmes and workshops, could be considered as another major obstacle towards the realisation of the standard in the area. Expertise in producing architectural details and drawings is needed, first, to execute the detailed building plans, and, second, to supervise the construction of Passivhaus buildings, ensuring that they are built according to the criteria of the Passivhaus standard and according to drawings. Furthermore, the skills of the construction workers are another issue to consider when endeavouring to build a Passivhaus project in the region. According to the QGBC head of sustainability, this was one of the challenges that the team faced in Qatar. Continuous supervision was needed in order to ensure that the work was executed as designed and, regardless of the continuous supervision; errors such as failing to properly seal pipe work resulted in the intended airtightness level not being achieved.

The concept of airtight buildings is associated with energy-efficient homes of the future; research has shown the importance of optimising the building fabric to levels that will ensure that energy is minimised and thermal comfort is maximised. The use of a mechanical ventilation system, therefore, is a strategy that should go hand in hand with airtight buildings to guarantee that human wellbeing and hygienic indoor environments are maintained. The introduction of the heat recovery ventilation system is associated with the Passivhaus standards, and it has been shown through a number of studies to be one of the issues repeatedly raised by the occupants. Therefore, operation of a ventilation system is expected to be a matter that the occupants of Passivhaus buildings will have to realise and possibly be trained for in order to effectively operate a Passivhaus building in Qatar and the region. Other aspects related to the heat recovery ventilation system that may have to be taken into consideration and may affect the implementation of the Passivhaus standard include the availability of the ventilation system itself in the local market, the actual knowledge related to the selection of the system and the heat recovery efficiency level. The availability and cost of other building components, such as high-performance glazing and cooling systems, may add concerns when re-thinking the Passivhaus standard for Qatar and the region.

The experiment of the PHV and the STV has demonstrated that close to Passivhaus standards are achievable in the area, and with further study and enhancements Passivhaus buildings could possibly be recognised in the area. It could be argued that the direct transition to the Passivhaus standard may be a giant leap in the region, especially when energy-efficient domestic buildings are not a common practice. Possible implementation of certain key features could initially ease the transition to the stringent standard. Through the presented research and its findings, a number of features, which have also been confirmed in work carried out by other researchers in the area (Alaidroos and Krarti, 2015; Taleb and Sharples, 2011), could be summarised as follows:

1. Prompting the concept of energy-efficient homes in the region, possibly by providing subsidies for low energy homes.
2. Re-considering the highly subsidised energy tariffs in the region, by possibly increasing tariff rates on high energy consumers in the residential sector.
3. Upgrading the glazing system, by implementing high-performance glazing such as triple-glazing systems.
4. Optimising the WWR based on orientation and natural lighting requirements.
5. Improving building regulation to include lower U-values to reduce solar gains and heat transfer.
6. Incorporating shading systems in the design, specifically towards opaque and transparent surfaces facing in directions that receive the most solar insolation.
7. Introduction of energy-efficient cooling systems, lighting and household appliances in the local markets.
8. Facilitating the integration of solar energy systems in the design of domestic buildings.

Finally, along with the previously suggested guidelines, and in order to progressively introduce the Passivhaus standard to architects and construction engineers in Qatar and the area, the following suggestions could be applied:

1. Possible collaboration with the PHI, or other Passivhaus qualified bodies at the beginning of implementing the standard in order to provide workshops and training programmes for architects, contractors and professionals in the region.
2. The creation of a Qatari Passivhaus web portal that provides information and updates about the Passivhaus standard and certified Passivhaus projects and best practices in the country.
3. The preparation of a list of certified Passivhaus materials, ventilation systems, cooling systems, glazing types, etc., that are available in the area, which could aid the designers in the selection process.
4. Continuous supervision should be carried out by architects and engineers on construction sites to ensure that architectural details are followed by the construction workers.
5. Passivhaus performance assessments and evaluations should be carried out to evaluate the actual success and acceptance of the standard in the country.
6. Full understanding of the climate and the architecture of the region and implementing passive design principles to the fullest may aid in the design of Passivhaus building as part of the Passivhaus approach.

7.6 Summary

"As the age of abundant cheap energy draws to an end, the consequences of accelerating climatic change and diminishing fossil fuel reserves have prompted a radical rethink about the need for energy efficiency in the built environment … Whilst buildings need to become more resource efficient, there is a concomitant requirement for them to become more resilient" (Hopfe and McLeod, 2015, xiv)

The Passivhaus standard has become one of the most widely spread energy-efficient standards around the world – almost 50,000 buildings have been built according to the stringent requirements of the standard. The meticulous detailing invested in craftsmanship of the standard and its criteria has urged many architects and building engineers to experiment with its adaptability in various climatic zones. A considerable number of studies have been carried out in Europe to assess the actual performance of Passivhaus buildings in the specific studied areas. Due to the fact that the standard originated in Germany, a number of studies have pointed out that there are challenges in implementing the standard in other countries. Some of the challenges were related to the understanding of the Passivhaus concept, such as overcoming difficulties related to overheating and passive cooling, while others were concerned with occupant satisfaction, such as being able to effectively operate the heat recovery ventilation systems, and the overall thermal comfort.

The Qatari Passivhaus project is the first in the region, and it is bound to face similar challenges once the house is occupied and fully operated. In the previous sections, the Qatari Passivhaus project was assessed in the light of other Passivhaus projects in hot climates. The Passivhaus standard in hot climates is achievable given the designer has a solid understanding of the standard concept and the specific climate. The presented case studies showcased that close to Passivhaus standards were achievable in hot climates and, with further monitoring and development, buildings could achieve Passivhaus certification in hot climates. The Qatari Passivhaus project was further assessed in comparison with the Passivhaus specific criteria for very hot climates. The PHV adhered to the Passivhaus criteria for opaque and transparent surfaces, but failed to fulfil two criteria – airtightness and specific primary energy demand, although the building is actually designed to be self-sufficient. Finally, the implications of applying the standard to domestic buildings in Qatar and the GCC were discussed and suggestions were made to ease the transition of the standard to meet the country’s building regulations.

The next chapter will conclude this research by identifying the main findings, the knowledge that has been gained, the limitations of the research, the final remarks and recommendations, and, finally, future research that can be conducted in this area.

Chapter Eight
Conclusion and Final Remarks

8 Conclusion and Final remarks

8.1 Overview

In this research, an attempt was made to explore the feasibility of applying the energy-efficient building typology, “the Passivhaus approach”, in the context of residential buildings in Qatar in particular and the GCC in general. This was accomplished through evaluating the performance of the first (ultra-low energy) Passivhaus building in Qatar. The assessment was completed by addressing the research objectives and the research questions stated in the introduction chapter, Sections 1.3 and 1.4. This chapter concludes the thesis, and begins by presenting a summary of the research area, followed by an illustration of the research significance, and the main findings and limitations, and finally it ends by recommending further work built upon the findings of this study.

8.2 Summary

Energy-efficient measures were introduced primarily as a response to the oil crises in the 1970s with the purpose of achieving energy savings in the built environment. In recent years, however, the concern has grown beyond energy savings. Now, it is also important to seek measures that reduce GHG emissions released into the atmosphere, and to ensure that a continuous supply of energy is secured for the future (GhaffarianHoseini et al,. 2013). A number of energy-efficient models have been built and tested in developed countries; in fact, some typologies are even included in future energy targets for a number of countries, such as low energy and zero energy buildings (Pittakaras, 2015). The quest to realise energy-efficient models in the GCC, however, is still in its infancy, with only a small number of models recognised and cited in the literature, one of which is the Passivhaus project in Qatar (Alalouch, Saleh and Al-Saadi, 2016).

The Passivhaus concept was initiated more than 25 years ago in Germany and has since spread widely in Europe. It is popular owing to its stringent requirements and its significant energy savings and high levels of thermal comfort. However, in Qatar and in the GCC region, the concept of energy-efficient homes is relatively new. Mandatory thermal codes are not strictly followed in the area, resulting in end users being less interested in applying energy-efficient measures. Additionally, the low energy tariff rates have contributed profoundly to limiting interest in pursuing energy savings within residential buildings. Through this research, the performance of the pilot Passivhaus project in Qatar was investigated and its outcomes discussed (Khalfan et al., 2015; Khalfan and Sharples, 2016b). The assessment process was carried out by conducting a comparative analysis between the performance of the two buildings in the project, the Passivhaus villa (PHV) and the standard villa (STV). The PHV was built following the Passivhaus criteria for the climatic conditions of Qatar, while the STV was scored as one star according to the GSAS rating system, which was adopted in Qatar in 2012. Three performance indicators were used to measure the performance of the PHV and the STV – energy use, thermal comfort and the thermal envelope performance. Both on-site measurements and simulation tools were utilised in the assessment process.

8.3 Research Significance

The significance of learning from the Passivhaus experience in Qatar arises from the fact that this is the first and so far the only Passivhaus project in the country and in the region. Additionally, this modular villa is considered to be one of the few known energy-efficient models within the residential sector in the GCC. Several studies have been carried out in Qatar and in the GCC to assess the effect of applying energy-efficient strategies to buildings in an attempt to achieve improved performance in the built environment. The studies targeted various outcomes, such as the reduction of the building's carbon footprint, or the achievement of additional energy savings, or the introduction of practices that mitigated GHG emissions. Many of these studies, however, are theoretical and were not able to achieve actual construction. The Passivhaus project in Qatar, therefore, provides a potential for actual evaluation of an ultra-low energy-efficient model that could be adaptable for the whole region. The experimental project allows the opportunity to measure the actual feasibility, energy savings, thermal comfort and the overall acceptance of the Passivhaus standard. Furthermore, this research demonstrated the potential energy savings associated with building according to the Passivhaus standard, not only for the present time but also for the future. This research, however, is only considered as a starting point, where an initial evaluation of the project has started and where possible future development can be resumed.

8.4 Research Main Findings

This section refers back to the hypothesis and the sub-questions listed in Chapter One, Sections 1.3 and 1.5. It recaps the research question and highlights the findings related to each by referring to the chapters that discussed the specific topic.

1. *What is the importance of introducing the Passivhaus standard as an energy-efficient model for Qatar?*

The answer to this question was provided within two sections in this research, the literature review within Part One, and the description of Qatar's energy policy in Part Two. The importance of introducing energy-efficient measures to buildings is not only a current concern but is also considered a future requirement for buildings. As stated earlier, energy saving is only one of the main aims of realising low energy models; other concerns such as mitigating the effects of climate change have gained much attention in recent years. The Passivhaus approach is considered to be one of the fastest growing energy-efficient standards; its basics are derived from a thorough understanding of how buildings operate and how energy within buildings could be minimised while delivering high levels of thermal comfort. Passivhaus buildings have been cited as one of the paths towards achieving zero energy buildings, which are today seen as the future of the housing stock in developed countries. The lack of such typologies in Qatar and in the GCC has initiated this research, and the Passivhaus approach was chosen as a result of its carefully engineered criteria and its renowned high performance levels.

2. *How to effectively measure the performance of the Passivhaus building and ensure that its predicted performance reflects the possible actual performance?*

The assessment tools and methods chapter within Part Two of this research has addressed the issues related to the methodology adopted in measuring the performance of the PHV and the STV. The IES-VE dynamic simulation tool was used to predict the performance of the villas. The results were validated through on-site temperature and relative humidity levels and sub-meter readings. The results representing the validation process were presented in the third part of the study, within Chapter Six, Section 6.2. Generally, a close agreement has been found in relation to the predicted and measured data, specifically for the PHV. The actual energy use measured through the sub-meter readings indicated a 20% lower energy usage when compared to the predicted total energy use in the PHV via IES-VE. This may be attributed to the fact that the villa was not occupied at the time, or to possible assumption errors in the simulation process. In the STV, very close proximity was evident between the measured and predicted total energy use; however, it should be noted that this may have been a result of the villa's partial occupancy. On the other hand, the indoor environment of the PHV was closely replicated in IES-VE, as the measured variables indicated close proximity for all living spaces. The STV thermal environment, however, did not provide similar outcomes; variations between the predicted and measured data were revealed. Therefore, through the validation process undertaken in this study by means of analysing the predicted and measured data, the performance of the Passivhaus model could possibly predict a close to actual performance.

3. *How well does the Passivhaus building perform in comparison to the standard building in the Passivhaus project Qatar?*

A full assessment of the PHV performance against the STV was demonstrated within Part Three, the performance of the villas chapter. The findings indicated that the PHV was expected to perform better than the STV in terms of energy use and thermal envelope performance, and be more consistent in terms of thermal comfort. The robust building envelope was responsible for lowering the heat gains to a significant level, allowing the PHV to be cooled with only one-third of the energy required to maintain acceptable indoor temperatures compared to the STV, and with a total energy demand of at least half the energy required to operate the STV. This finding was tentatively confirmed through the sub-meter readings: the total annual energy use in the STV was twice more than the measured energy use in the PHV, while the cooling demands were almost three times as much as the cooling demand in the PHV. Furthermore, the whole load of the PHV could be met by the energy generated via the PV panels. Acceptable thermal comfort levels were maintained in both villas, although a better consistency throughout the different seasons and hours of the day was noticed in the PHV based on the thermal models used. The field measurements confirmed this finding; more consistent hourly temperatures and relative humidity levels were recorded in the PHV, while the STV showed more variable hourly measurements. In addition to the reduction in energy and cooling demands in the PHV, the operative temperatures of the living spaces were predicted to be 3°C lower than the STV without active cooling. This suggests the significant role of the building thermal envelope to both reduce energy demands and maintain a better indoor environment.

4. *If the Passivhaus building was expected to perform better than the standard building at the present time, how well is it expected to perform under the impact of climate change?*

The performance patterns predicted and validated for the present-day scenario were replicated throughout the future scenarios. The findings were illustrated in Section 6.4 of the performance of the villas chapter. The PHV was likely to continue consuming around 60% less energy than the STV, with an energy use increase factor (ratio of future to current energy use) of 1.1 compared to the preceding timeline scenario for both villas. The cooling demands of the STV were expected to increase with time by a factor of 4.6 and reach 5.6 in comparison to the PHV cooling demand for the three timeline series. The full load of the PHV would still be met in the future by the energy generated by the PV panels. Thermal comfort would be maintained at acceptable levels in the two villas, although a slight discomfort in the STV was predicted, mainly for one of the inhabitable spaces (LIV), and partly for one of the bedrooms (BR 2). The thermal envelope was likely to continue performing effectively by maintaining the indoor operative temperature of the PHV below the extreme outdoor dry bulb temperatures, although the differences between the STV and the PHV indoor operative temperatures were estimated to increase between 2-3°C in the future, compared to the current scenario.

5. *What key features of the Passivhaus building can be transferred to local buildings to improve their performance and sustainability?*

This aspect was addressed in Parts One and Three of this research, as part of the quest to assess the performance of the Passivhaus project in Qatar. Through the literature review presented in Part One, it was evident that the building's fabric contributed significantly in achieving energy savings and reducing GHG emissions. Parametric studies have been carried out in various contexts suggesting that buildings are expected to achieve better energy and thermal performances if the outer fabric is optimised (De Boeck et al., 2015; Harvey, 2013; Li, Hong and Yan, 2014).

Similarly, the success of the Passivhaus is built on the notion of achieving buildings that are highly insulated and airtight to obtain reductions in energy and attain high levels of thermal comfort. For the future-proofing of buildings, the same approach for the building fabric needs to be undertaken. In this research, a parametric study was conducted to upgrade the performance of the STV, Section 6.5. The main findings of the study indicated that upgrading the building fabric, by increasing the insulation level of the opaque and transparent surfaces, was responsible for reducing energy demands by 20% and cooling demands by 50%.

This leads to the conclusion that more consideration should be paid to the building fabric in Qatar in order to reduce the cooling loads and ultimately achieve additional energy savings, and more specifically to the transparent surfaces, which are the most vulnerable elements of the building fabric. The Passivhaus standard requires very tight envelopes; similarly, many studies suggest that the buildings of the future need to be more airtight. Although the Passivhaus in Qatar did not meet the Passivhaus criteria, it is still probably considered one of the most energy-efficient residential buildings in Qatar, and has proved to achieve additional energy savings and steady thermal comfort when compared to the standard building.

6. *Are Passivhaus buildings expected to be more comfortable than standard buildings, given that people are expected to acclimatise to higher comfort temperatures in hot regions?*

Based on the Passivhaus institute literature, Passivhaus buildings are expected achieve high levels of thermal comfort given that they are executed according to the Passivhaus criteria. However, various reports have been raised about discomfort in Passivhaus buildings, mainly due to overheating in summer within cooler climates. Other issues related to the indoor environment being unsatisfactory in terms of unpleasant odours and poor ventilation have been cited in a few studies. Some of these studies have been summarised in Part One of this research within the Passivhaus standard chapter, Section 3.4 (Mahdavi and Doppelbauer, 2010; Junghans and Berker, 2014; Thunshelle and Hauge, 2015; Rohdin, Molin and Moshfegh, 2014; Ridley et al., 2013).

According to the findings of this research, both the PHV and the STV have achieved acceptable levels of thermal comfort, although the PHV was slightly better and more consistent in maintaining indoor thermal comfort. This result agrees with the findings of the study conducted in Austria by Mahdavi and Doppelbauer (2010), where the thermal comfort levels of Passivhaus flats was found to be slightly better when compared to the thermal comfort achieved in the low energy flats. Another risk that has been repeatedly raised is the risk of overheating, but this may not pose a risk in Passivhaus buildings in hot climates due to the fact that cooling systems would normally be sized to sustain continued thermal comfort. However, it could be argued that, with occupants acclimatising to higher temperatures, more savings can be anticipated by adjusting the cooling set points to higher levels.

Another risk may be associated with stuffiness or moisture problems in the indoor environment. Although a few studies have directly pointed out this risk, others have raised concerns about the operation of the ventilation system, which ultimately would lead, if not operated properly, to this problem. In Qatar, as the villas were not occupied at the time, this risk was not assessed thoroughly, but, based on simulation, the PHV in Qatar was predicted to need humidity control to ensure continued comfort in the future. Additionally, based on the measured indoor temperature and relative humidity levels, the PHV maintained the indoor temperature between 22°C and 23°C, and the relative humidity levels between 50% and 60% in the bedroom spaces during the hottest weeks, and between 21°C to 24°C and 50% to 75% in the living space during the cooler months.

7. Has the Qatar Passivhaus villa actually met the German Passivhaus criteria?

As stated earlier, not all criteria have been met in the PHV. Through the various assessment means conducted in the villa performance chapter, the following areas failed to meet the criteria:

- The building infiltration rate: the airtightness level was measured by using a blower door test at 50 Pas n_{50}. The results indicated that the PHV was above the Passivhaus benchmark. The measured airtightness level was 0.9 ACH, whereas the airtightness level of Passivhaus buildings is expected to be 0.6 ACH or less.
- The primary energy demand, according to IES-VE results, for the PHV was predicted to consume around 21,000 KWh annually. However, the estimated measured energy annual energy use was around 13,000 kWh, almost two-thirds less than the predicted total energy use. Direct comparison to the Passivhaus primary energy demand may not be feasible due to the fact that the Passivhaus Primary energy demand calculations include the embodied energy and is considered based on the treated floor area. Therefore, if the primary energy factor is factored into the figures presented above, it could be assumed that the PHV would exceed the Passivhaus primary energy benchmark. However, through the use of PHPP and the assumption of using best practices for building components and appliances and, and the application of solar glazing and high-definition framing systems, the PHV was estimated to use around 106 kWh/m^2.a.

Although the above Passivhaus criteria were not met, the building's opaque and transparent surface U-values and the indoor thermal comfort criteria were met. This indicates that, with further considerations and precision in building element selection, and with meticulous detailing and execution, the Qatar PHV could have reached the Passivhaus standard.

8. How does the Passivhaus villa performance compare to that of a conventional residential building in Qatar?

In this research, the performances of conventional buildings were not thoroughly investigated, but rather other studies and estimates were referred to. Furthermore, through literature and based on correspondences with officials involved in the building sector in Qatar, it was evident that minimum protection to building shells was practised in Qatar. Currently, there are no binding laws that enforce the use of thermal insulation and glazing types in residential buildings, but rather the recent building guidelines suggests maximum U-values for walls and roofs, window-to-wall ratios and double glazing for commercial buildings (KAHRAMAA, 2016). Government buildings, on the other hand, have been following the GSAS rating system since its initiation in 2012 (Lahn, 2013).

The World Bank database estimated that energy use per capita in buildings in Qatar was around 15,471 kWh per capita for the period between 2011-2015, while Meier, Darwish and Sabeeh estimated the energy use per capita for conventional buildings in Qatar at 14,000 kWh per capita (Meier, Darwish and Sabeeh, 2013; World Bank, 2016b). The PHV was estimated to use only use one-third of the amount of energy required for a conventional building. Additionally, based on the measured sub-meter readings, the PHV could actually achieve even further energy savings. The Qatari Passivhaus experiment provided a promising example for energy savings in the area, and the assessment indicated that the building had reached close to Passivhaus standards. Therefore, with further study and development, additional savings could be possible. Furthermore, the PHV has demonstrated better performance that a one-star-rated building on the GSAS rating system: it has incorporated the use of renewable energy sources for hot water and electricity use, and has adhered to many features that are associated with buildings of the future, such as airtightness, extensive insulation, mechanical ventilation and the use of energy-efficient appliance and goods. Thus, the performance of the PHV is no doubt far more advanced than that of a conventional building, not only for the present time but also for the future.

9. *What are the barriers that may be associated with the implementation of the Passivhaus concept in Qatar?*

Through the literature review and the previous experiences of Passivhaus buildings in different contexts, mostly within Europe, several implications could be predicted for the case of Qatar. Possible implications and suggestions have been listed in the discussion chapter, within Part Three of this research. A number of studies presented within the first part of this study have indicated that occupants of Passivhaus buildings were confused when operating the ventilating system (Junghans and Berker, 2014; Brunsgaard, Knudstrup and Heiselberg, 2012). This led to problems such as overheating or uncomfortable indoor spaces. Another study pointed out that the actual execution of the building was not as anticipated through design, and Passivhaus criteria, therefore, could not be met (Raidea, Kalameesa and Mauringb, 2015). A third study pointed out that there were financial burdens associated with building to the Passivhaus standard, which was not found to be feasible when compared with the financial expenses of constructing a low energy building in the same context (Audenaert, De Cleyn and Vankerckhove, 2008).

Finally, another review showcased that buildings were more successful in adopting Passivhaus concepts in Germany and Austria as a result of mutual architecture, technology and first adoption of the standard (Müller and Berker, 2013). For the project in Qatar, it is expected that similar issues would arise. Occupants would be faced with the new concept of ventilation systems due to the airtightness requirement, and when not operated effectively indoor discomfort may become an issue. Other aspects related to the needed knowledge, expertise and technology differences may pose other obstacles. Finally, the investment costs associated with the adoption of the Passivhaus standard may not be justified given the highly subsidised energy tariffs. Challenges and implications experienced in the Qatar Passivhaus project experience agree with some of the findings and observations listed above, including:

- The experience of designing to the Passivhaus standard is relatively new to the area. This is evident in the Passivhaus project as the assigned design team that were responsible for detailing the PHV were based in London.
- The PHV was not as airtight as required or designed, and several issues related to construction detailing had caused this infiltration problem. Airtightness detailing

has not been a common skill within the construction community in the area, and may pose a challenge towards achieving Passivhaus criteria.

- The availability of ventilation systems in the local market and the knowledge to make an informed choice on the most effective system.
- The availability and feasibility of energy-efficient appliances in the local market.
- The added costs of constructing according to the Passivhaus standard, and the absence of enforcement laws that impose energy efficiency within the residential sector.

As a conclusion, and by referring to the thesis hypothesis; in theory, the Passivhaus standard could be applicable as a low energy standard in Qatar. However, through the assessment carried out in this research, evidence has shown that close to Passivhaus standards were achievable. It should be pointed out that the lack of occupancy was one on the main shortcomings of this assessment process. Occupant behaviours are highly unpredictable and may have a considerable effect on the outcomes of this research. Additionally, other obstacles as stated in sub-question 9 above restrict the feasibility of applying the standard at the present time; this includes the lack of expertise, higher associated capital in comparison to the low energy tariffs, and finally the absence of enforcement laws.

8.5 Research Uncertainty and Limitations

The scope of this research was limited to the assessment of a single Passivhaus building in the context of Qatar. Assessment indicators were also restricted to three aspects – energy use, thermal comfort and the performance of the thermal envelope. The boundaries set by this research were undertaken partly due to available resources and the data that could be collected on-site. Other virtual examples of building types, sizes and forms could have been included, but, as the project is considered to be the first in the area, it was felt that more focus should be given to analysing the Passivhaus experiment. Assessing the performance of the Passivhaus villa, and comparing it with the neighbouring standard villa, allowed first-hand insight into how the Passivhaus building could perform in the hot climate of Qatar.

Additionally, the choice of the assessment indicators was based on the Passivhaus concept and the availability of validation through real-time measurements.

This research attempted to present the possible energy performance and thermal comfort of the PHV. As this is an individual case, then the results cannot be generalised, and variable outcomes could result from other projects in the future. However, an indication of the possible performance could be perceived. The nature of the research itself is bound with a number of limitations, some of which have been discussed in the assessment tools and methods chapter within the second part of this study. This includes the nature of simulation outcomes, which are governed by a number of assumptions and inputs such as the generated weather files, assumptions associated with the occupancy patterns and household appliances usage, and the thermal properties of the materials used in the project. Another uncertainty is related to the simulation outputs of the future scenarios and the associated generated future weather files. Future scenarios by nature are based on assumptions built on how the future may unfold. In this study, the A2 SRES emission scenarios used were generated using weather generation tools. The scenarios are based on future GHG trajectories based on demographic, technological, social and economic development.

In addition to the uncertainty related to the simulation outcomes, there are further limitations associated with the validation process. Energy use was only validated through three sub-meter readings, and further statistical interpolations were necessary to estimate the annual energy use. Additionally, the measured indoor temperature and relative humidity levels in the STV specifically and the living spaces in both villas showed erratic readings when compared to the simulation predictions. This could have been due to the possible manipulation of the set point temperature or positioning of the data loggers or even errors in the HVAC assumptions made during simulation.

This study also lacked post-occupancy evaluation (POE) studies, which could have added more depth to the assessment of the PHV. A POE could have provided a better understanding of how different the Passivhaus experience, in terms of thermal comfort, general acceptance and ease of operation, might be compared to the standard residential dwelling. In addition, a POE would have addressed issues that have been raised through post-occupancy studies in Passivhaus buildings, such as stuffy environments, indoor air quality and operation of the ventilation system.

Finally, inconsistencies were found when comparing the results obtained from PHPP and IES-VE in term of the cooling loads and total primary energy demand. The discrepancies that resulted were due to two main reasons: (1) the nature of calculations embedded in each tool, and (2) the different assumptions made in each tool. Owing to the lack of technical data, best practices and certified Passivhaus elements were assumed in the PHPP model, resulting in differences in results. Furthermore, when comparing the measured estimated energy use and IES-VE results, a difference of around 20% was noticed in the PHV, while the STV showed very close proximity to the measured energy use. This was, as stated earlier, possibly partly due to the assumptions made in IES-VE or as a result of lack of occupancy.

While the results presented in this study are individual to the specific case study and cannot be generalised, they have provided indicators towards the possible performance of Passivhaus buildings in the hot and arid climate of Qatar and the GCC. Additionally, the implications of constructing to the Passivhaus standard have been highlighted and suggestions have been made based on the literature review and the specific Passivhaus experiment.

8.6 Further Work and Final Remarks

As the Passivhaus concept is new to the area, there are many research opportunities that could be undertaken at this stage. Some of these have been listed under the Passivhaus experiment scientific partnership presentation (Amato and Skelhorn, 2014), such as:

- The solar power generated through the PV panels and the implications to transfer the surplus loads to the national grid.
- The study of heat flow in the building as a result of the extensive insulation and shading systems used.

- The water savings associated with the use of a grey water system for irrigation and toilet flushing.
- The assessment of the embodied energy related to the construction according to the Passivhaus standard, in comparison to conventional practices.
- The justification of the additional construction capital and payback period.

Additionally, further studies could be carried on based on this research, such as:

- Fully modelling the PHV in PHPP, while incorporating all the technical details of the PHV as close to the as built.
- Carrying out post-occupancy evaluation studies to assess the actual thermal comfort and overall occupant experience in the Passivhaus project.
- Additional monitoring and further on-site measurements could be considered to better understand the performance of the Passivhaus building while occupied.
- Future weather files could be generated in relation to the new IPCC RCP scenarios.
- Further parametric studies could be carried out to evaluate various types of Passivhaus buildings, such as commercial or educational buildings, or even different residential building forms and sizes, such as apartment buildings or two-floor villas.
- Further detailed study in relation to the implications of implementing the Passivhaus standard.

Although the Passivhaus standard originated in Germany, it has spread to different parts of the world. This study has demonstrated the possible performance of the first Passivhaus building in Qatar. It has showcased a possible template for design strategies that could be applied in the region to realise Passivhaus buildings. The design approaches adhered to the Passivhaus criteria for the specific climatic conditions and agreed with scholars' recommendations for Passivhaus buildings in hot climates. These include: (1) a highly insulated and airtight building fabric, (2) high-definition glazed surface, (3) reflective building surfaces, (4) the introduction of various shading systems and (5) an effective ventilation system (Cotterell and Dadeby, 2012; PHI, 2015b; PHI, 2015a; PHI, 2015c; IEA, 2013a). The significance of the latter-mentioned strategies has been confirmed in the design of the PHV and through the parametric study that was conducted to upgrade the performance of the STV.

This study has concluded that close to Passivhaus standards were achieved in the PHV and has suggested that, with further development and careful detailing and understanding of the Passivhaus concept, Passivhaus buildings could be achieved in Qatar. Lastly, the study has touched upon the possible implications that may be associated with the implementation of the Passivhaus standard in Qatar, with the most significant linked with the highly subsidised energy tariffs in the country.

The Passivhaus approach is said to be the basis for future-proofing buildings. It has been considered, "*an essential prerequisite template for ultra-low energy buildings*" (McLeod, 2013, pg. 208). Therefore, to prepare for, and to cope with, the trends of the future buildings, it is essential to understand how they work today and develop the template to withstand future climates.

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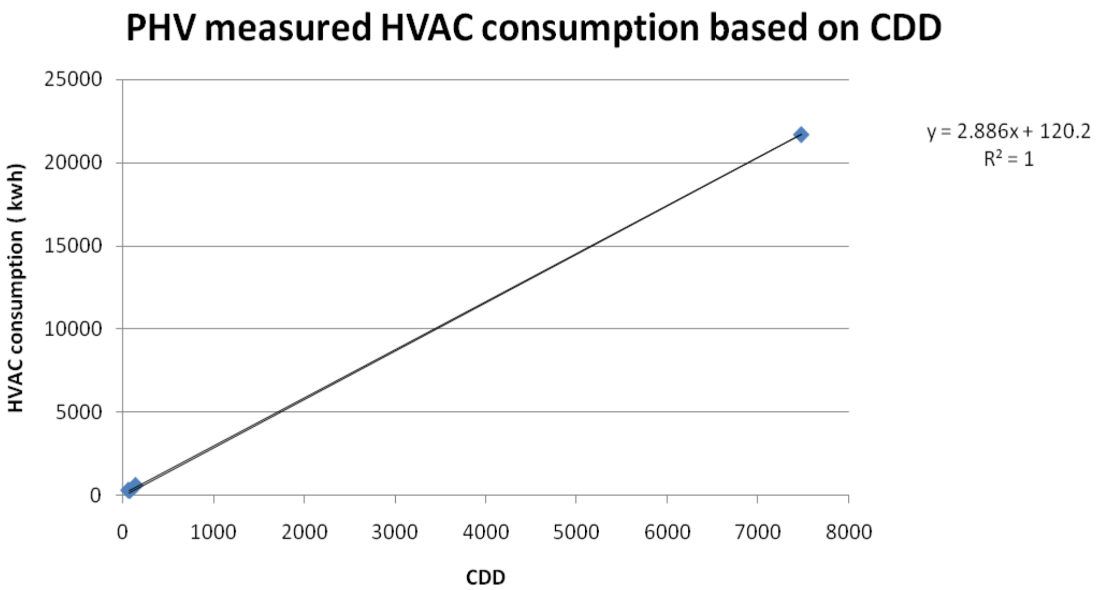
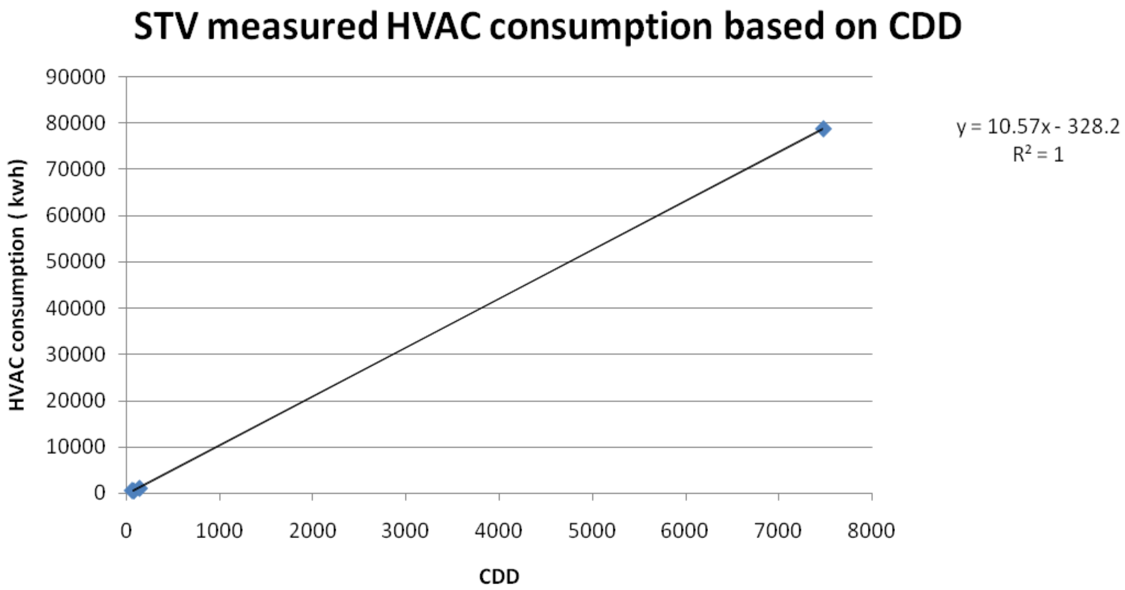
Appendix A



PHV measured HVAC consumption based on CDD
25000
20000
15000
10000
5000
0
HVAC consumption (kwh)
0
1000
2000
3000
4000
5000
6000
7000
8000
CDD
y = 2.886x + 120.2
R² = 1



STV measured HVAC consumption based on CDD
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
HVAC consumption (kwh)
0
1000
2000
3000
4000
5000
6000
7000
8000
CDD
y = 10.57x - 328.2
R² = 1

Appendix B

Passive House Verification

Building:	Qatar Passivhaus Project
Street:	e
Postcode/City:	4 e
Province/Country:	doha QA-Qatar
Building type:	Residential
Climate data set:	ud---01-Standort 1
Climate zone:	7: Very hot Altitude of location: -
Home owner / Client:	QGBC
Street:	
Postcode/City:	
Province/Country:	

Architecture:	AECOM	**Mechanical system:**	Dunkun
Street:		Street:	
Postcode/City:		Postcode/City:	
Province/Country:		Province/Country:	
Energy consultancy:		**Certification:**	
Street:		Street:	
Postcode/City:		Postcode/City:	
Province/Country:		Province/Country:	

Year of construction:	2013	Interior temperature winter [°C]:	20.0	Interior temp. summer [°C]:	25.0
No. of dwelling units:	1	Internal heat gains (IHG) heating case [W/m²]:	2.4	IHG cooling case [W/m²]:	2.7
No. of occupants:	4.0	Specific capacity [Wh/K per m² TFA]:	60	Mechanical cooling:	x

Specific building characteristics with reference to the treated floor area

			Value		Criteria	Alternative criteria	Fullfilled?[2]
	Treated floor area	m²	156.0				
Space heating	Heating demand	kWh/(m²a)	0	≤	15	-	yes
	Heating load	W/m²	-	≤	-	-	
Space cooling	Cooling & dehum. demand	kWh/(m²a)	57	≤	27	60	yes
	Cooling load	W/m²	10	≤	-	10	
	Frequency of overheating (> 25 °C)	%	-	≤	-		-
	Frequency excessively high humidity (> 12 g/kg)	%	0	≤	10		yes
Airtightness	Pressurization test result n_{50}	1/h	0.6	≤	0.6		yes
Non-renewable Primary Energy (PE)	PE demand	kWh/(m²a)	106	≤	-		-
Primary Energy Renewable (PER)	PER demand	kWh/(m²a)	51	≤	45	51	yes
	Generation of renewable energy	kWh/(m²a)	191	≥	60	64	

[2] Empty field: Data missing; '-': No requirement

I confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The PHPP calculations are attached to this verification.

Passive House Plus? yes

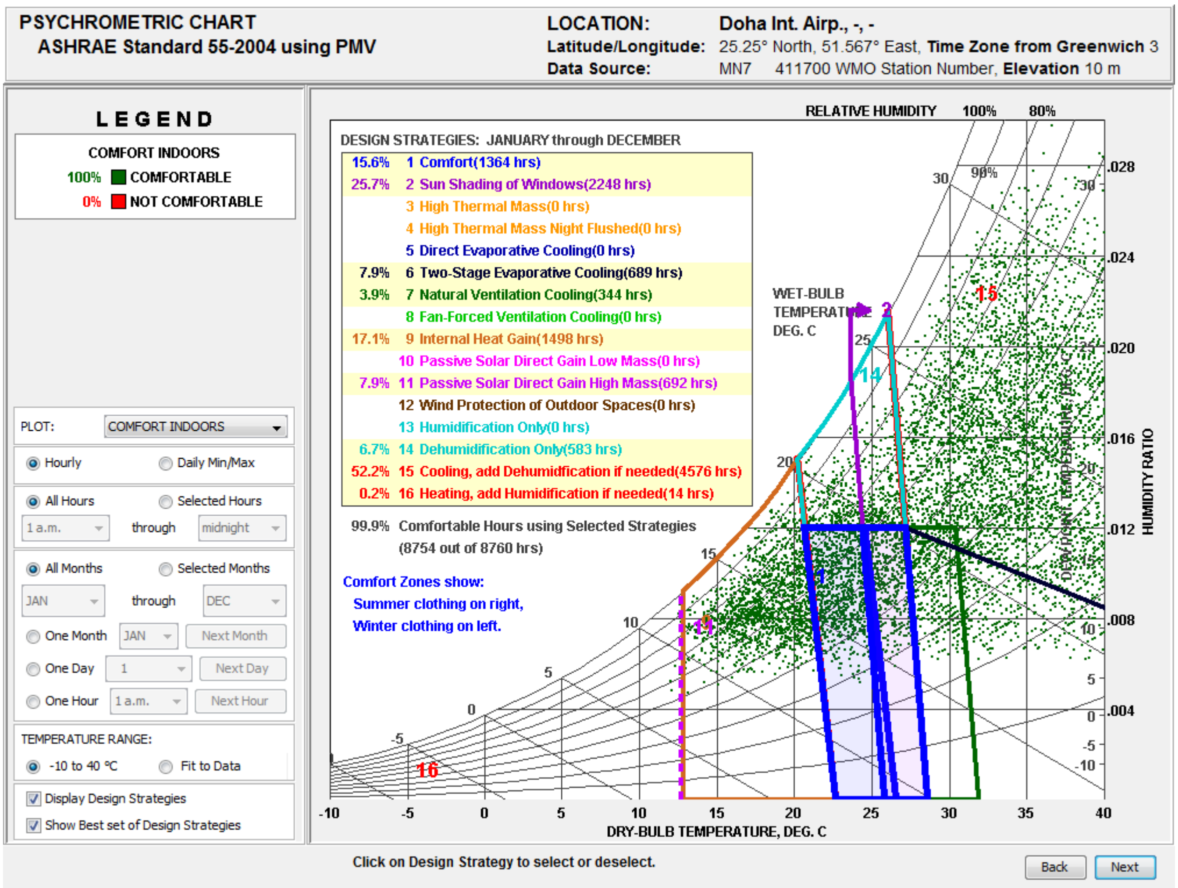
Task: First name: Surname: Signature:

Issued on: City:

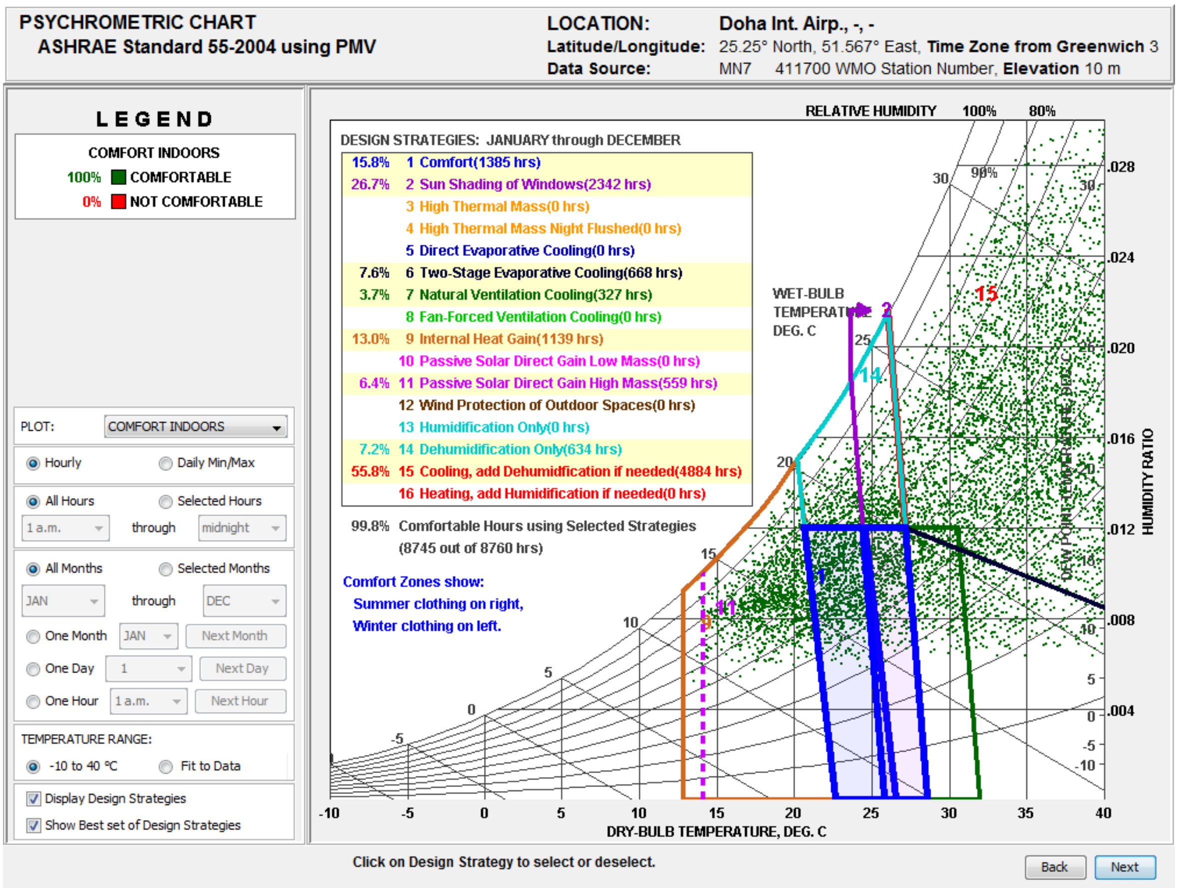
PHPP, Verification   PHPP_V9.3a_EN_PHV.xlsx

Appendix C

Climate Consultant psychrometric chart for 2020 weather file



Climate Consultant psychrometric chart for 2050 weather file



Appendix D

List of Publications

1. PLEA 15 conference (2015) in Bologna, The first Passivhaus in Qatar: initial monitoring and modelling energy performance.
2. SBE 16 conference (2016) in Dubai, Thermal comfort analysis for the first Passivhaus project in Qatar.
3. Journal of Sustainability paper (2016), The Present and Future Energy Performance of the First Passivhaus Project in the Gulf Region.